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Development of Bench-Scale Settling Apparatus: Settling Velocity Data for Design and Operation of Wet-Weather Flow Solids-Liquid Separation Processes

Interim Report

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Development of Bench-Scale Settling Apparatus: Settling Velocity Data for Design and Operation of Wet-Weather Flow Solids-Liquid Separation Processes

by

Thomas P. O'Connor, David Fischer and Richard Field
Water Supply and Water Resources Division
National Risk Management Research Laboratory
Edison, New Jersey 08837
U.S.A.

John Cigana, Benoît Gagné and Martin Couture
John Meunier Inc.
Montreal, Quebec H4K 1K5
Canada

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Project Officer
Richard Field
Urban Watershed Management Branch
Water Supply & Water Resources Division
National Risk Management Research Laboratory
Edison, NJ 08837

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

The information in this document has been funded by the United States Environmental Protection Agency under CRADA No. 136-96. It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document. Mention of trade names or commercial products does not imply endorsement by the United States government. This document was originally an internal report, intended for internal Agency use only.

Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risk from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective, environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

This study is a side-by-side comparison of a traditional settling-column particle-settling-velocity distribution evaluation method and a new settling evaluation method. This portion of the study investigates whether these column tests are capable of capturing or representing the rapidly settling particles present in wet-weather flows (WWF). Equipment for the two testing methods was fabricated and laboratory tested and preliminary evaluations were made. This interim report reviews the sampling procedures and analytical methods used and presents data and results. Laboratory tests were conducted with well characterized settling media, in order to measure suspended solid (SS) concentrations and develop settling distributions on known substances in the columns prior to testing actual WWF which exhibits variable SS concentrations and settling distributions. The main purpose of this ongoing study is to obtain design data for WWF SS separator treatment devices, e.g., vortex separators, grit chambers and settling tanks.

A summary of the performance as measured by predicted percent removal of both columns for 15 laboratory tests is presented, as well as a comparison of the advantages and shortcomings of the two methods.

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Acknowledgments

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1. INTRODUCTION

Background

This Interim Report pertains to the laboratory evaluation of a field-testing apparatus developed by the Centre d'Enseignement et de Recherche pour la Gestion des Ressources Naturelles et de l'Environnement (CERGRENE) of France which uses several small columns to measure particle-settling velocities. This method was adapted for North American application by John Meunier, Inc. The settling-velocity distribution and pollutant content may be used for wet-weather flows (WWF) treatment process selection and design and for evaluation of preliminary or existing process operation.

The U.S. Environmental Protection Agency (EPA) National Risk Management Research Laboratory's Water Supply and Water Resources Division, Urban Watershed Management Branch in Edison (UWMB), New Jersey and John Meunier Inc. in Montreal, Quebec, Canada, established a Cooperative Research and Development Agreement (CRADA) (136-96) to develop settling columns suitable for obtaining particle settling-velocity distribution data for WWF. John Meunier, Inc. and the UWMB are jointly responsible for the prototype apparatus design, construction, testing, and field evaluation as well as procedures to significantly improve selection, design, and operation of full-scale WWF treatment processes that depend on solids-liquid separation through settling and vortex separation. This CRADA will compare the new apparatus with the larger traditional column, the advantages and disadvantages of each method, the projected standard operating procedures, QA procedures, expected results and the limitations for both settling-velocity distribution tests for WWF.

The newer settling testing method is thought to be more amenable to field use because of ease of transport and sampling, and the limited number of samples generated. The comparison attempted to predict whether these tests can capture the solids in WWF, particularly the rapidly settling particles, and whether both systems provide similar design information. Measurements of suspended solids (SS) for several settling times were used to compare the methods. A summary of each column's performance as measured by percent removal for 15 laboratory bench-scale tests is presented and the two methods are compared.

This study is a side-by-side comparison of an existing settling-testing method and a newer settling-testing method. The ongoing study is attempting to determine whether these tests are capable of capturing or representing the rapidly settling particles present in WWF. Two separate column testing methods were fabricated and laboratory tested and preliminary evaluations were made. This interim report reviews the sampling procedures and analytical methods used and presents data and results. Well characterized particles were used in the lab to measure SS concentrations and develop settling-velocity distributions in the columns prior to testing WWF, particularly combined sewer overflow (CSO), which has extremely variable SS concentrations and settling-velocity distributions.

This study was planned in three phases:

- **Phase I:** Preliminary screening - Conducted in a laboratory setting to identify experimental parameters and determine process variables using well characterized particles. Aspects of this phase were performed by both parties (UWMB and John Meunier, Inc.). Procedures were then adjusted to allow for any difficulties encountered during this phase.
- **Phase II:** Laboratory bench-scale testing - The official QA approved experimental test runs of the side-by-side analysis of this phase were conducted in the laboratory of the John Meunier, Inc.
- **Phase III:** Field study - Side-by-side comparative study of the two settling characterization methods (conventional and CERGRENE) will be conducted at an offsite location with actual CSO samples. This side-by-side comparison will determine the limitations and advantages (e.g., cost, setup requirements, correlation to actual settling [in a primary sedimentation tank]) of each approach. Onsite settling column sampling will better represent settling velocities because sample storage and transport may change the naturally occurring settling velocities. Samples will be delivered immediately to the UWMB laboratories and analyzed for SS and other parameters. The Perth Amboy, New Jersey treatment works has been confirmed by both parties for the sampling of CSO.

Objectives

The monitoring and analysis needed for proper selection application, assessment, design, and evaluation of WWF treatment are expensive, time consuming, and complex; however, reliable data collection may save even more costly construction costs by eliminating unnecessary facilities and/or additional controls. The particle-settling-velocity distributions of WWF samples as related to total solids and SS and associated pollutant content are essential for proper assessment of high-rate settling and vortex separation technologies.

The objective of this study is to compare sampling and analytical procedures of two settling column techniques used to characterize the settling velocity of SS in WWF. These results will aid engineers in obtaining pertinent WWF pollution-abatement facility selection and design data by analyzing particle-settling-velocity distribution, and settleable, suspended, floatable fractions and design parameters. These design parameters include facility dimensions, overflow rate, design flowrate, detention time and predicted removal efficiencies.

Low cost, expedient methods to obtain facility-design data or settling-velocity distributions are necessary because WWF characteristics are highly site specific. In order to test the viability of the newly developed CERGRENE columns, a comparison to a settling method with a precedence was needed. Thus a traditional column settling method was used..

Combined Sewer Overflows

The recent EPA National Combined Sewer Overflow Control Policy (59 Federal Register 18688) (CSO Policy) guidance "Combined Sewer Overflow - Guidance for Nine Minimum Controls" (EPA, 1995) requires:

- maximization of flow to the publically owned treatment works (POTW) for treatment
- control of solid and floatable materials in CSOs

and "Combined Sewer Overflow - Guidance for Long-Term Control Plan" (EPA, 1995) further requires:

- characterization, monitoring, and modeling activities as the basis for selection and design of effective CSO controls
- evaluation of alternatives that will enable the permittee, in consultation with the National Pollutant Discharge Elimination System (NPDES) permitting authority, water quality standard (WQS) authority, and the public, to select CSO controls that will meet clean water act (CWA) requirements
- cost/performance considerations to demonstrate the relationships among a comprehensive set of reasonable control alternatives
- maximization of treatment at the existing POTW for wet weather flows

The CSO Policy recommends control/treatment without defining the need for analysis of the flow characteristics and constituents to obtain design information. Determining certain flow characteristics and constituents will optimize the selection and design of unit processes for various degrees of existing physical treatment, e.g., vortex separation, screening, sedimentation, flocculation-clarification, dissolved air flotation, and filtration, and assist in the assessment of newer technologies, e.g., microcarrier coagulation-sedimentation processes. Site specific, storm-event data evaluations are needed for designing CSO treatment facilities, as CSO differs from dry-weather flow (DWF). CSO settleable solids build up and characteristics in the sewer system are a function of the length of the antecedent dry-weather period, sewer slope, drainage area (catchment) size, flowrate, and drainage area soil characteristics, etc., whereas DWF solids characteristics (barring industrial sources) are similar from place to place. Furthermore, suspended and settleable solids concentrations can vary with time during the storm events and from storm to storm.

Past studies have identified urban stormwater runoff as a major contributor to the degradation of many urban lakes, streams, and rivers. Industrial and commercial parking lots, material storage areas, and vehicular service stations are the most significant contributors of a variety of pollutants to WWF. Chebbo et al. (1990) found that the fine particles which make up the majority of SS are also the principal vector of pollution in stormwater during wet weather. Fine particles (< 50 μm) found in stormwater can achieve settling velocities of 2.5 m/h (0.07 cm/s) or more (Chebbo et al., 1990) and 70% to 80 % will deposit within 15 min and more than 97 % after 1 hr.

Settling Columns

The traditional settling method for determining settling-velocity distributions uses side ports to analyze quiescent sampling. Camp (1945) published settling curves using Stoke's Law based on particle settling and Eckenfelder (1966) used it as a design aid for sedimentation

processes and for analysis of flocculation. There is substantial variability associated with this method (hereafter Long column).

Currently, only one method for measuring gravity separation is accepted by Standard Methods[1] (SM 2540.F.b; 19th Edition) called "settleable solids". However this method neither determines particle-settling velocity nor enables calculations for settling-velocity-distribution curves. This gravimetric method only measures the initial and final SS concentration after 1 hr. There are no control limits or substantiating data for this method.

This method uses a column of at least 20 cm in depth. A sample is pipetted from the center of the column after 1 hr of quiescent settling to determine the nonsettleable solids. Settleable solids are equal to the initial SS concentration minus the nonsettleable solids concentration.

Traditional Column

The typical Long column is a relatively large apparatus (Camp (1945), Eckenfelder (1966), Dalrymple et al. (1975), in addition to being described elsewhere), standing 1.8 to 2.5 m (6 to 8 ft) high with a diameter of 20 to 30 cm (8 to 12 in.) with side withdrawals evenly spaced along the column depth. The height of the column simulates the effective settling depth which occurs in a sedimentation tank that typically has constructed depths exceeding 2.5 m (8 ft). This column requires an extensive laboratory layout. Various methods have been used to pre-mix the sample before the column test begins, e.g., plunger plates and rotation of the settling column. Depending on specific dimensions between 40 and 80 L (10 and 20 gal) are required to fill the column. The water height in the column is measured. The samples, withdrawn from the side ports sequentially from top to bottom at predetermined time intervals, require further SS analysis. After each set of samples is collected, the depth of the water in the column is measured.

The most notable difficulty with the Long column method is the inability to develop a homogeneous initial SS concentration at the intial samplig time, t_0, due to the heavy particles in WWF. This is partially caused by the length of time required to fill the column and the time required to withdraw samples from all ports sequentially. Pisano et al. (1984) went to the extent of mounting the Long column on a device that allowed axial rotation in an attempt to achieve a better estimate of SS concentration at t_0. It is almost impossible to have a homogeneously mixed sample at t_o using the classical settling column for WWF, which may result in predictions of lower than actual SS fractions.

CERGRENE Columns

CERGRENE (Chadirat et al., 1997) developed a new design that uses a sequence of small columns to analyze the particle settling velocities. Instead of sampling various fractions, with a single sampling device, the CERGRENE protocol uses different settling columns. The

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[1] Standard Methods describes other settling methods which are applicable to the zone settling of sludges. Sludges have significantly higher SS concentrations and different characteristics than CSO.

CERGRENE settling columns, like the long column, are designed to sample for SS concentrations of the WWF in the original sewage matrix.

The new CERGRENE columns have a shorter time to fill (approximately 7 s) and may be more completely mixed at the initial sample time (better representation of t_0). It is thought that the CERGRENE column may account for a wider range of settling solids which may result in establishing better design parameters for WWF. The CERGRENE column was designed for field as well as laboratory use. Settling-velocity-distribution samples taken in the field should give a truer representation of the settling rates of the combined sewage. Settling velocities of samples taken in the field should be faster than samples taken back in the lab or stored in the lab for longer periods of time due to less time allowed for agglomeration.

Other Columns

Other methods developed in Europe are:

Brombach or German (Michelbach and Wöhrle ,1993 and Pisano and Brombach, 1996);

Norwegian Institute for Water Research (NIVA) (Lygren and Damhaug, 1986 and Walker et al., 1993); and

University of Aston U.K. (Tyack et al., 1993)

These methods were specifically designed for the relatively high concentration of heavier particles in storm-generated flows and accordingly, offer several benefits over the Long column. They require less analyses, yielding one sample per time measurement withdrawn from the bottom as opposed to several simultaneous samples from the multiple-side ports. These devices use smaller testing volumes, approximately 4 to 12 L (1 to 4 gal). This is especially true of the German and the NIVA columns (less than 1 m deep and 5 cm wide) which are also more amenable to field use. The Aston column stands at least 2.2 m tall and requires more assembly than the other two as it rotates about the center of the column. These methods provide truer representation of high settling-velocity SS because the concentrated sample is situated above the settling column and dropped into it at t_o.

Unlike the Long and CERGRENE settling column designs which sample the WWF mixture, the Brombach and NIVA methods separate, dry and then reintroduce the SS into clean water. The Aston column was previously tested directly against various forms of the CERGRENE column (Aiguier et al., 1995) which suggested that the derived settling-velocity curves from the various innovative methods tend to give different results. For this reason, only the long and the CERGRENE columns will be analyzed for the purposes of this project.

Theory of Settling Design

Several factors are used in the design of a settling basin including design flow, required detention time and desired percent removal. The first two factors alone could be used to design the physical dimensions of a basin, however, once the third factor is included, the characteristics of the SS in the WWF must be taken into account. For sedimentation tanks Tchobanoglous and

Burton, 1991), the design velocity V_c (m/s) can be related to the liquid depth, D (m) in the tank and the detention time, t_d (s) as follows:

$$V_c = D/t_d \quad (1\text{-}1)$$

Given a certain flow through the settling tank, Q (m^3/s), and the plan area of the tank, A (m^2), V_c (m/s) can be related to the overflow rate, q ($m^3/m^2/s$ or m/s), in the following manner:

$$V_c = q = Q/A \quad (1\text{-}2)$$

This assumes that all SS with a settling velocity greater than V_c or *q* will be removed with some fraction of all other particles also being removed. For the purposes of this project, the overflow rate will be used in the graphs as a surrogate for a design settling velocity, instead of V_c, which inherently implies a single design settling velocity for a particle instead of a settling-velocity distribution.

Settling can also be broken down into the four types of settling: discrete, flocculant, hindered, and compression (Tchobanoglous and Burton, 1991). The settling velocities of discrete and flocculant particles are of most concern with respect to WWF. The hindered and compression zones of settling are issues of high concentration waste streams, which typically occur at a POTW in secondary-settling tanks and sludge-handling devices or industrial applications.

Various studies used discrete settleable solids and various column devices or settling methods to determine settling velocities. In Stoke's Law (Equation1), the velocity of an ideal sphere is proportional to the square of the particle diameter.

$$v_s = g(\rho_s - \rho)d^2/(18\mu) \quad (1\text{-}3)$$

where:
v_s = velocity of sphere, m/s
g = acceleration due to gravity, 981 m/s^2
ρ_s = density of the particle, kg/m^3
ρ = density of the fluid
d = diameter of sphere, m
μ = dynamic viscosity, $N \cdot s/m^2$

As previously mentioned, settling columns have been used to observe and analyze flocculant settling. WWF is often a combination of discrete and flocculant settling.

While direct measurement of sedimentation efficiency can be made on controls after installation by taking grab samples at the influent and effluent of the controls, the settling column and its predicted removals can assist the engineer or scientist in the selection of design parameters before installation for WWF storage and treatment facilities. Settling columns can

help determine the settling velocity distributions for local conditions, e.g., silty WWF may require larger facilities for a desired percent removal, while gritty waste streams could achieve the same percent removals with much smaller facilities. Onsite analysis of this overflow rate derived from the observation of the actual settling velocity distribution is a better design component than the assumption derived from Stoke's Law which only relies on the settling of discrete particles.

In Field Sampling

Sampling devices must be able to capture the heavier SS or settleable solids and not manifest biased results due to stratification. For an automatic sampling device, this means that its intake velocities and ports must be greater than the mainstream velocity and be placed at multiple levels in order to capture the heavier particles near the channel invert, respectively.

The importance of in-field sampling is related to the change in settling properties due to storage and transport. In a comparison of two tests, Dalrymple et al. (1975) showed that two distinct Long column tests had different results on two consecutive days, even though both were run on the same sample. The difference in the test was attributed to the storage of the sample for 24 hr for the second test. This difference in stored samples was also confirmed by CERGRENE (Aiguier et al., 1995), when a fresh sample was compared to the settling rates of three samples stored for 24-hr at different temperatures (room, refrigerated and frozen). Each sample, all collected at the same time, had different settling distributions.

Field Test Site

In identifying field sites for Phase III, the UWMB and John Meunier, Inc., looked for municipalities ready to share technical information regarding location and configuration of combined sewers and overflow sites. The municipalities needed to supply information on drainage area (preferably residential to minimize influences due to industrial sources), the number and volume of overflows per year, SS concentration of overflows and frequency distribution of overflow events. Ideally, candidate sites would not yet have identified or installed treatment options for their CSO's. Additionally, the municipalities would have to be willing to permit the project team access to their facilities during CSO events in the summer of 1999 and to publish results based on data collected.

The City of Perth Amboy, New Jersey operates a combined sewer system and wastewater transfer pumping station that collects combined sanitary sewage, industrial wastewater, and storm runoff from an approximately 7 km^2 drainage area to a regional wastewater treatment plant owned and operated by the Middlesex County Utility Authority. The wastewater transfer pumping facility is located at the junction of Water Street and Sadowski Parkway. A CSO regulator is located about 6 m (20 ft) below the Sadowski Parkway with an overflow weir and 2 m (7 ft) diameter CSO tide-gated outfall to the mouth of the Raritan River.

The pumping station inflow is from the interceptor that discharges into one of two wet-wells each equipped with a mechanical coarse bar screen for removing large debris and

protecting the sewage pumps. The screen chamber inflow may be utilized for settling studies, since the inflow is a part of the CSO and will have the same characteristics at the outfall point during storm events. The wet-well is approximately 9 m (30 ft) deep. This is an enclosed facility with 24 hr access and a person on duty. Grit which accumulates in the wet-well is removed from the facility once every three months. A winch and two pumps are also available. This location is approximately five miles away from the UWMB in Edison, NJ.

Field Sampling Review

As background for this project John Meunier Inc. reviewed and wrote an internal report (Champigny et al., 1997) on the state-of-the-art of field-sampling practices. This field of expertise is often overlooked in studies and generally considered as a secondary subject. It was a weak point in many recent characterization studies. The objective of this assessment review was to evaluate the importance of the variability of solids found in sewer systems and to identify the most reliable method to obtain representative samples from a combined sewer. While many of the methods analyzed in the assessment were not developed for the study of WWF, the following general conclusions and recommendations are from the complete internal report were made:

- In dry weather conditions, the vertical concentration gradient of SS can be related to the flow velocity pattern in the pipe or channel.
- A first flush phenomenon has been observed by some researchers.
- Sediments found at the bottom of the channels interact with the SS and have to be included in the sampling.

Two separate sampling systems were recommended:

1. Sampling a complete section of the flow from bottom to top, or
2. Placing sampling port intakes at two points.

This second method would mount one sampling point just above the level of the dry weather flow, near the pipe walls. The second sampling point would be maintained at 60% of the total water level throughout a WWF event.

2. MATERIALS AND METHODS

The design and fabrication of the columns was conducted in the EPA UWMB facility in Edison, NJ and in the offices of John Meunier, Inc. in Montreal, Quebec, Canada.

Column Description and Delivery

The Long and CERGRENE columns were fabricated and preliminary evaluations were conducted by the EPA and the John Meunier, Inc., respectively. In phase I, different types of particles were tested to select the best media to be used in the benchtop laboratory studies and to answer other questions including sampling and analysis procedures, and experimental parameters and number of samples. In phase II, a set of 15 experiments was conducted in John Meunier's Laboratory from June 9, 1998 through June 17, 1998.

Long Column

The accepted settling-velocity distribution determination methods in the United States have commonly employed 1.8 to 2.5 m (6 to 8 ft) columns to study settling characteristics of solids. The EPA designed an eight-foot modular column fashion which allows for several assembly and sampling configurations (Figure 2.1). The column is made from cast acrylic tubing with an 203 mm (8 in.) outer diameter, a wall of 6.5 mm (0.25 in.) and 190 mm (7.5 in.) inner diameter. The column consists of four separate modules: a base section, a 1.2 m (4 ft) section, and two 0.6 m (2 ft) section and allows the column to be set up in a 1.2., 1.8 or 2.5 m (4, 6, or 8 ft) configuration. The 1.2 m (4 ft) section must be attached to the base. The volume of the column is approximately 70 L (18 gal). The modules are attached by acrylic flanges with foam gaskets to eliminate leakage. A cap is also available to prevent foreign material from entering the top of the column.

Sampling ports (125 mm [0.5 in] NPT thread) equipped with quick disconnect fittings with flow size diameters of 9.5 mm (0.375 in.) are located every foot, on either side of the column, for a total of 16 ports at eight depths. Sampling from both sides of the column is meant to yield a more representative sample of the contents, minimizing "wall effects" and increasing the sampling area. It was originally thought to be more important to sample from both sides toward the bottom of the Long column where the sample flows are highest than at the top where samples flows are smaller due to decreased head. The base section includes a one inch diameter drain which is connected to a three-way valve. This valve is used for filling and draining the column. A conical plastic piece (funnel) is installed above the drain inside the column to facilitate resuspension of solids during the filling process and aid clean out between tests. A wooden baffle screwed into the cone disperses the flow and keeps the influent well-mixed.

Filling is accomplished by pumping from a mixing basin through the bottom valve. Before filling, the pump is primed, and the bottom valve turned to "fill." Prior to and during filling, the mixing basin (described later) stirs the solids to keep them suspended. After filling, the pump is turned off and the bottom valve is turned to the middle position. Sampling from the side ports can then proceed.

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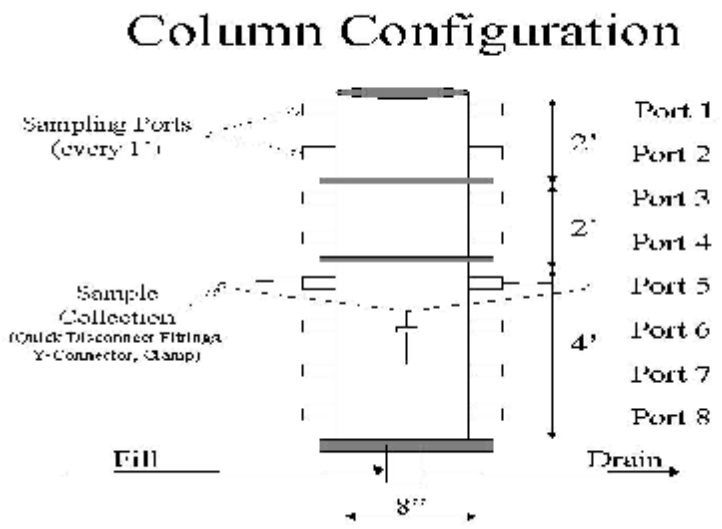


Figure 2.1 Long Column General Arrangement

Sampling tubes are attached to a male quick disconnect fitting at each sampling port. For two-sided sampling, two tubes attached to male quick disconnect fittings lead to a T-connector which is attached to a short tube. This short output tube brings the sampling streams together. Sampling from the end of this output tube is controlled by attaching another set of quick disconnect couplings.

Sampling is initiated at the top of the column, and progresses downward for each time interval. Each sampling tube are purged before sampling. The output tube is placed in the plastic bottle marked "Purge," and a male pipe adapter is attached to an elbow hose barb. The "Purge" bottle is filled to a measured marking and then in midstream the tube is quickly moved to a plastic storage bottle. Each plastic storage bottle is marked with an individual identification number which is recorded along with the corresponding port (1, 2....8) and sample time. After sufficiently filling the plastic storage bottle, the male quick-disconnect adapter is removed from the output tube. Storage bottle size was nominally 250 ml which appeared to match the 10 - 20 mg target mass range for SS analysis for the media in Phase I. Cold storage was not required for Phases I and II as the samples contained inert material (e.g., sand and clay). Storage requirements that address the specific types of analysis for combined sewer samples which will be taken in Phase III are presented in the Work/QA plan.

CERGRENE Column

CERGRENE, the Centre technique international de l'Assainissement, Centre d'Expertise en Gestion des Eaux d'Orages (CEGEO, a subsidiary of John Meunier, Inc.) and the University of Aston undertook a study to optimize settling velocity distribution measurements. The objectives of this study were to:

- Compare the results of existing methods and protocols on identical samples;
- Compare and contrast the advantages of each method; and
- Understand the influence of each parameter (settling height, column diameter, concentration of SS, temperature, etc.) on the settling velocity distribution.

In light of the study results, a new column test was proposed to meet the following criteria:

- the sample should not to be pretreated;
- the sample should remain in its original matrix (water and SS) for tests;
- a sufficient sample size should be collected for analyses;
- the column should be easy to use; and
- the column should be compact for in-situ measurements.

The resulting settling test was the CERGRENE columns. These were tested with a prototype and then in full scale. John Meunier, Inc. constructed four replicas of the CERGRENE column based on equipment available in North America. The column is constructed of 65 mm (2.5 in.) inner diameter clear PVC and stands approximately 1 m (3 ft) tall. The volume of this column is approximately 2.2 L (0.55 gal). The column (Figure 2.2) has three valves located at the top, the bottom and the middle. The middle valve, a 65 mm (2.5") inner diameter ball valve, is approximately 2/5 of the length from the bottom and divides the column into two sections.

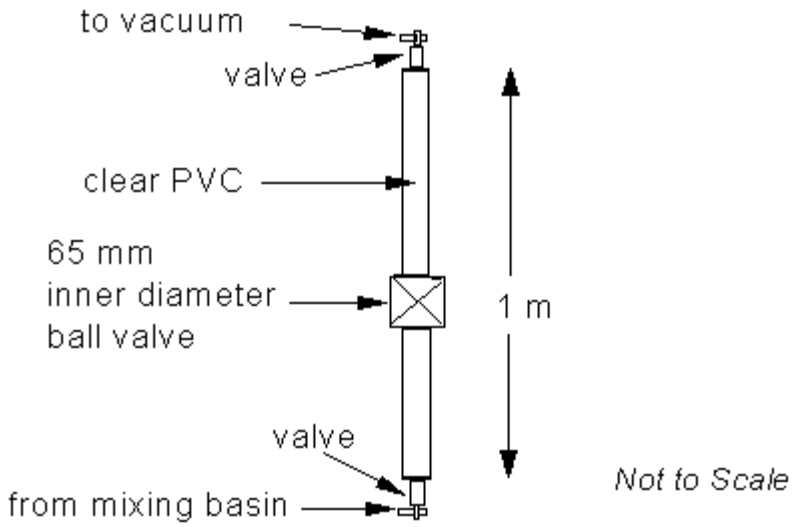


Figure 2.2 CERGRENE® Column Configuration

The column is filled by vacuum aspiration to minimize the variation of SS concentration between the bottom and top sections. An advantage of a vacuum pump is that it doesn't break SS apart as readily as a typical positive displacement water pump which tends to grind up and shear particles thereby changing the settling characteristics. After filling, the top and bottom

valves are closed. At the specified sampling time, the two sections are separated by turning the middle ball valve. The bottom portion is the sample. This volume of approximately 1 L (0.25 gal) is drained and SS analysis is performed. As previously discussed, the major premise for performing this comparison is to determine whether the CERGRENE column provides truer representation of high-settling velocity SS at the test starting time, t_0, than the Long column.

Each CERGRENE column is sampled independently at discrete times and represents one sample for settling-velocity distribution analysis; this differs from the Long column which requires multiple samples to be taken per time interval. Filling of the columns is conducted sequentially. Results from Chebbo et al. (1995) indicated that sequential filling of the columns did not significantly impact results.

Mixing Basin

The mixing basin is 0.66 m (2 ft) in diameter and 1.3 m (4 ft) high, and has a 300 L (80 gal) holding volume. Four vertical baffles were inserted at 90° intervals to prevent the formation of a vortex (Dickey and Hemrajani, 1992; and Etchells et al., 1992). The mixer is mounted on a sawhorse above the basin. The mixer shaft is in the middle of the basin and two impellers are used, i.e., a marine impeller at the bottom and Rushton impeller above.

A marine impeller with three blades was placed about 1 cm (0.4 in.) from the bottom of the basin to create an axial flow in the basin, provide complete mixing of fluids and suspend particles that may settle naturally (Dickey and Hemrajani, 1992; and Etchells et al., 1992). The mixer manufacturer (Greey Lightnin) recommended a 25.4 cm (10 in.) diameter impeller based on the existing basin configuration. The Greey Lightnin' mixer, model XJ-43 with1/3 hp of power, has a constant mixing velocity of 350 rpm.

The use of a Rushton impeller is based on previous mixing studies done by John Meunier, Inc. (Gagné and Bordeleau, 1996) and was also verified by the CERGRENE group (Chadirat et al., 1997). The dimensions of the Rushton impeller (four equally spaced 60 mm wide by 90 mm tall paddles) were also linked to the physical dimensions of the basin. The Rushton impeller creates an axial flow that keeps the particles suspended by the marine impeller well mixed throughout the basin. During Phase I, the Rushton impeller was tested at 20 cm (8 in.) above the marine impeller.

CERGRENE showed that mixing velocities of 200 rpm and 600 rpm were adequate to generate complete mixing in the basin and achieve the similar results (Chadirat et al., 1997). The mixer was turned on 15 min prior to and stayed on throughout sampling.

During the experiments, the mixing basin was filled with an initial SS concentration of 300 mg/L. On the sixth side-by-side experiment, the volume in the mixing basin was changed from 200 L to 250 L and the initial mass of 60 g of media was increased to 75 g to maintain the known concentration at 300 mg/L. This extra volume prevented the water level from falling too low which caused excessive vibration in the mixer after filling the Long column.

Sampling

The Long column and CERGRENE system were filled from the mixing basin in an alternating sequence. The point of withdrawal was 7 to 10 cm (3 to 4 in.) from the wall, set halfway between the baffles and at an alternating height of 18 to 35 cm (7 or 14 in.) from the bottom which maintained a volume of water in the basin throughout a test. The alternating sequence for filling and height of withdrawal were intended to reduce bias in the experiment as described in Experimental Design.

Long Column

The Long column was sampled at only four of the potential eight port depths in the actual side-by-side comparison to increase the number of samples that could be obtained at different times and depths in the first few minutes of sampling. Samples taken from the top of the column required more time, i.e., 7 s at Port 1 in Figure 2.1 when the column was full, while samples taken from the bottom six ports had sufficient head to ensure a shorter sampling time period, i.e., < 3 s at Port 3 and below. Also, if all depths were sampled there would not have been enough sample for the top ports for the later times. An analysis of discharge velocities from the ports showed good correspondence to theoretical values.

The fill time of the Long column ranged from 69 to 76 s for a height of 0.24 m (95 in.) On average the upflow velocity of water in the 10 out of 15 experiments where both height and time were measured was 3.3 cm/s.

For each set of Long column samples (one set = samples from ports 3, 5, 7, and 8), average decrease in water height in the column was 4.5 cm (1.8 in.), averaging 1.1 cm (0.45 in.) per sample. These average values were used to adjust the depth of the Long column in the calculation of overflow rates. The decrease in water level height for one set includes both purge and sample volume.

CERGRENE Columns

The vacuum pump filled the CERGRENE columns in an average of 8.2 s. Using a standard height value of 0.91 m (3 ft) for the columns the uplfow velocity was approximately 11 cm/s. The slowest filling time was 11.5 s which was most likely a function of a cold start of the vacuum pump. Even for this scenario with a worse case sample height of 0.76 m (2.5 ft), the upflow velocity in the CERGRENE would exceed 6.6 cm/s. The upflow velocity in the CERGRENE column is at least twice as fast as the Long column.

The CERGRENE columns were never actually filled to capacity, always being a little short from the top. This height of the sample level in the CERGRENE columns is measured for calculation of the settling-velocity distribution. Problems with the sample height measurement of the upper chamber of the CERGRENE columns are discussed in Chapter 3.1.2 and specific recommendations and a CERGRENE institutional modification are presented in Chapter 4.

Suspended Solids Analysis

Suspended solids was the critical measurement of these experiment. Table 2.1 presents the summary of Standard Methods used. The selection of analytical methods is based on the following priority:

1. Standard Methods, 19th Edition.
2. EPA Method

Table 2.1 Summary of Standard Methods and Procedures

Parameter	Sample Type	Method No.	Method Title	Source
Suspended Solids	Water	2540 D	Total SS Dried at 103-105 °C	Standard Methods
Settleable Solids	Water	2540 F	Settleable Solids	Standard Methods

The upper limit for SS sample sizes is 200 mg of residue. The lower limit for SS is 4 mg/L as specified by EPA method 160.2.

SS was calculated by the following procedure:

$$\text{mg suspended solids / L} = \frac{(A - B) \times 1000}{\text{sample volume, mL}} \qquad (2\text{-}1)$$

where: A = weight of filter and dried residue, mg and
B = weight of filter, mg.

The grain size of the particles for the laboratory experiments exceed the filter paper pore size (1.5 µm, Whatman 934-AH) of the filters being used for the SS analysis. For the laboratory experiments, 47 mm diameter filters were used; this may be switched to 70 mm diameter filter for the raw wastewater samples to be taken in the field as recommended by Standard Methods.

To perform settleable solids, a graduated cylinder was filled from the pump used for the Long column. After one hour, a 250 mL sample was siphoned from the approximate center of the graduated cylinder and was analyzed for SS. This was the nonsettleable solids. This concentration is subtracted from the initial SS concentration as derived from separate samples. As settleable solids is an extension of SS analysis, the same limits apply.

Settleable solids is calculated by the following method:

mg settleable solids / L = mg suspended solids / L - mg nonsettleable solids / L (2-2)

Identification of Experimental Materials

Initial experiments were performed using microsand, Foullon's Earth, glass beads and natural soils. The media were mixed in tap water prior to introduction into the mixing basin.

Microsand was chosen to test the mixing basin and for the laboratory experiments. The characteristics of the microsand used for the testing were :

d_{10} = 85 μm
d_{60} = 125 μm
ρ = 2.62 g/cm^3

The calculated settling velocities for these parameters using Stokes Law (ideal sphere assumed) are <1 cm/s, which is less than the upflow velocities measured in the columns.

A surficial soil excavated from near Princeton, New Jersey, was also used as an additional reference. The soil (Neshaminy) is a silty clay loam, containing 17% sand, 46% silt, and 37% clay. Although this soil has a greater proportion of very small particles, it also has a wider variation, with d_{10} = 75 μm and d_{60} = 700 μm. (Fischer, 1995)

An analysis of the microsand by a Coulter® LS Particle Analyzer determined the following particle diameters:

d_{10} = 156.2 μm
d_{50} = 232.8 μm

This analysis was performed in January, 1999 after the Phase II was complete.

Experimental Design

Table 2.2 shows the original experimental design of the side-by-side test to account for differences due to the order of filling the columns and variations in the height of the mixing basin. One duplicate was performed for each medium (microsand, Neshaminy and mixture) for a total of fifteen runs. The run order was randomized to reduce bias due to one soil type being repeated and to reduce influence of "learn as you go" increased precision.

Table 2.3 provides a prototype sampling strategy for microsand. A set of samples from the Long column will be withdrawn at specified intervals (e.g., 1 min, 3 min, 5 min, 10 min) with time measurements to the nearest second for the individual sample end-times. One set of samples for the Long column comprises four samples. For each CERGRENE column, the valve is turned to capture SS at a time corresponding to one time "set" for the Long column. The initial time for the individual CERGRENE column shall be designated $t_{0,i}$ where i represents the number of the column. The time for the CERGRENE column is the time from the moment each column is filled to the time the sample is isolated by turning the valve of each column. The Long column t_0 was the time that filling was completed, and initial concentration was assumed to be background or "recycle" concentration as taken from the mixing basin by the pump as explained in Chapter 3.

Table 2.2 Experimental Design for Laboratory Test

Media	Run #	Randomized Run # Order	Withdrawal Height (cm)	Column Filling Order	End Time (min)
Microsand	1	8	18	Long / CERGRENE	10
Microsand	2	15	36	Long / CERGRENE	10
Microsand	3	4	18	CERGRENE / Long	10
Microsand	4	13	36	CERGRENE / Long	10
Microsand	Duplicate - 13	12	18	Long / CERGRENE	10
Clay soil	5	5	18	Long / CERGRENE	60
Clay soil	6	10	36	Long / CERGRENE	60
Clay soil	7	14	18	CERGRENE / Long	60
Clay soil	8	1	36	CERGRENE / Long	60
Clay soil	Duplicate - 14	6	36	Long / CERGRENE	60
Mixture	9	9	18	Long / CERGRENE	60
Mixture	10	11	36	Long / CERGRENE	60
Mixture	11	3	18	CERGRENE / Long	60
Mixture	12	2	36	CERGRENE / Long	60
Mixture	Duplicate - 15	7	18	CERGRENE / Long	60

Table 2.3 Typical Critical Time Measurements for One Run of Microsand

CERGRENE Column		Long Column				
Initial Time	Time	t_0 - initial time	Port 3	Port 5	Port 7	Port 8
$t_{0,1}$	$t_{0,1}$	< 1 min	$t_1 - t_0$	$t_2 - t_0$	$t_3 - t_0$	$t_4 - t_0$
$t_{0,2}$	1 min - $t_{0,2}$	< 2 min	$t_5 - t_0$	$t_6 - t_0$	$t_7 - t_0$	$t_8 - t_0$
$t_{0,3}$	3 min - $t_{0,3}$	~3 min	$t_9 - t_0$	$t_{10} - t_0$	$t_{11} - t_0$	$t_{12} - t_0$
$t_{0,4}$	5 min - $t_{0,4}$	~5 min	$t_{13} - t_0$	$t_{14} - t_0$	$t_{15} - t_0$	$t_{16} - t_0$
$t_{0,5}$	10 min-$t_{0,5}$	~10 min	$t_{17} - t_0$	$t_{18} - t_0$	$t_{19} - t_0$	$t_{20} - t_0$
Duplicate - $t_{0,x}$	x min - $t_{0,x}$	Cannot perform Duplicate on Long column				

A similar table to Table 2.3 could be constructed for the Neshaminy soil and other particle mixtures, with the time of the samples extended out to one hour. The estimated settling rate limit of Microsand d_{10} 80μm < 15 min Long and <10 min for CERGRENE.

Since only four CERGRENE columns were available for the five or six required tests for each run, the first two CERGRENE columns were sampled, rinsed out and refilled from the mixing basin during Phase II. This procedure was used for the first nine test when it was discovered that the CERGRENE columns were producing random settling results. Then only one CERGRENE column was used for the remaining six experiments, and the column rinsed out after each individual test.

Ideally, any variation caused by the mixing and separation of flows was not expected to exceed values already determined in Phase I. Figure 2.3 shows the lab setup.

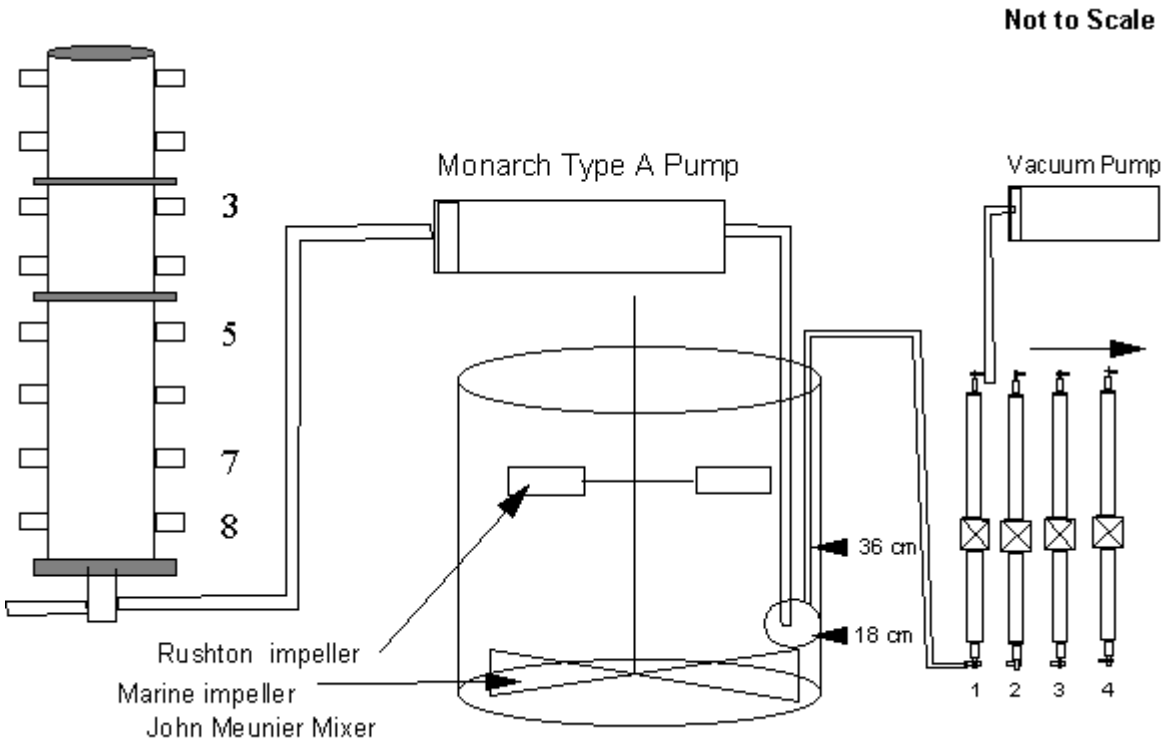


Figure 2.3 Configuration for Side-by-Side Field Analysis

3. RESULTS

All figures for this section are presented in the appendices (e.g. Figures A-1 - A-5 are in Appendix A, Figures B-1 - B-32 are in Appendix B)

Quality Control Analysis

Several levels of testing procedure were incorporated to address quality control in the Phase II analysis.

Blanks and Standards

Method blanks were run either on de-ionized, tap, or basin water before the delivery of the media. The purpose of blanks was to ensure the cleanliness of SS analysis. All blanks showed concentrations below 4 mg/L (Figure A-1).

The accuracy of the SS procedure was determined from the analysis of laboratory control samples whose true values are known. Standard reference materials (SRM) were the same materials used in the experiments, namely, microsand, Neshaminy silty clay loam, and a 50-50 mix of the sand and Neshaminy. In phase III, diatomaceous-silica will be used as the SRM. Table 3.1 specifies the quality control standard concentrations and the expected recoveries for diatomaceous-silica.

Table 3.1 QA Objectives for Measurements

Measurement	Method	Reporting Unit	Initial Concentration	Standard Deviation	Relative Standard Deviation	Complete-ness
Suspended Solids	2540D	mg/L	15	5.2	33%	90%
			242	24	10%	90%
			1707	13	0.76%	90%
Settleable Solids	2540F	mg/L	NA	NA	NA	NA

Accuracy is expressed as percent recovery. The formula used to calculate this laboratory QC values for a SRM is:

$$\%R = 100\% \times C_m / C_{srm} \qquad (3\text{-}1)$$

where: %R = percent recovery
C_m = measured concentration of SRM
C_{srm} = actual concentration of SRM

Excluding two extremes, the average percent recovery was 83% with media results of 76%, 83% and 88% for sand, mixture and clay, respectively.

Figures A-2 through A-5 show an analysis of the measured standards versus the expected percent recovery (the log linear line in all the graphs) for diatomaceous silica as developed from the values for relative standard deviation in Table 3.1. To plot a comparison versus the relative standard deviation values in Table 3.1, %R was adjusted by subtracting from 100% to get relative percent difference (RPD) values.

Figure A-2 shows RPD for all the media and Figures A-3 through A-5 are media specific. The Neshaminy (Figure A-5) exhibits the best RPD, equivalent to expected recoveries of diatomaceous silica. The mixture (Figure A-4) had several RPD within acceptable limits but for most cases exceeded the limits of diatomaceous silica by up to 45%. The microsand (Figure A-3) exceeded the expected RPD for diatomaceous silica in all but one case.

The microsand was the most difficult media to work with when performing SS, as particles tended to stick to the surfaces of analytical equipment due to water tension. The analysis of microsand produced the most pronounced losses. Neshaminy soil was much easier to analyze (except when the filters began to clog) as the results indicate. Except for one extreme outlier of -189% for a mixture sample (A-4) which represented a gain in mass, all SRM analysis indicated a loss in SS.

Another factor that may have contributed to this error in the SRM was the smaller sample sizes, 125 mL bottles, while Long column sample were 250 to 300 mL and CERGRENE samples were 250 mL for Neshaminy and 960 mL for the microsand and the mixture.

Completeness

The completeness is defined for this study as the ratio of the number of valid measurements to the total number of measurements planned for each parameter. A completeness objective of 90 percent is expected to ensure that sufficient valid data are collected to evaluate the settling velocity distributions. Table 3.2 shows the completeness for critical SS measurements made for all 15 test. The formula used to determine completeness is:

$$\%C = 100\% \times V/T \qquad (3\text{-}2)$$

where % C = percent completeness
V = number of measurements judged valid
T = total number of measurements

The Recycle and the Standard Methods samples are the only sample types that do not achieve the completeness criteria of 90% in Table 3.2. However, they approach 90 %, and are within one sample of passing this criterion.

As noted in Table 3.2, only 17 of the 340 long column samples were disqualified for faulty measurements (e.g., sample volume not noted). Additionally, three microsand samples fell below the 4 mg/L limit of detection for the EPA SS method, though these samples appear in the graphs as approaching zero concentration, or 100% removal.

Table 3.2 Completeness of Suspended Solids Analysis

Type or location	Total Samples	Voided Samples	Expected Completeness	Measured Completeness
Blanks	17	0	90%	100%
CERGRENE	101	0	90%	100%
Long	340	17	90%	95%
Recycle	45	5	90%	88.9%
Standard Methods	16	2	90%	87.5%

Of the 101 separate CERGRENE samples, none of the samples were voided. However, in lieu of incomplete information, when omissions in measurement could not be deduced, standard values were assumed. These values had to do with measured volumes of the CERGRENE column. The bottom of the column was assumed to be 960 mL, which did not vary noticeably when measured directly, and in fact should not have varied at all, as the bottom portion was filled to capacity. After the first few runs, it was decided more error was introduced by measuring than assuming the 960 mL value. The default bottom volume of 960 mL was used in calculating the upper chamber volume and percent removals, but the measured volume was used for actual SS concentration of the bottom effluent.

Due to faulty recording procedures, height measurements, which represents the volume of the top chamber in the CERGRENE columns, were not recorded for several individual CERGRENE runs. This measurement was not critical at the time of the laboratory analysis but became more critical during analysis of the settling velocities using CERGRENE's iterative matrix program. Where no height measurement was available, a value of 41.9 cm (16.5 in.) was used. This value is the mode for the 86 out of 101 samples for which a height measurement is available, with a mean of 41.4 cm (16.3 in.), a standard deviation of 1.7 cm (0.65 in.) and a coefficient of variance (CV) of 0.040. As the test proceeded, better control of the level in the CERGRENE columns was exhibited. For experiments 10 through 15, which are the only acceptable CERGRENE experiments, the mode was 41.9 cm (16.5 in.), the average was 42.1 cm (16.6 in.), with a tighter standard deviation of 1.3 cm (0.53 in.) and CV of 0.032 for fewer samples (31 of 40 samples). Measurements could only be made to the nearest eighth-inch, which implies a virtually identical mean and mode.

The error introduced by the lack of height measurements is minor in comparison to other sources. The major cause of variability in the SS analysis was the use of the microsand itself. During sample preparation, sand could be observed clinging to the filter housing, and was subsequently scraped onto the filter. This was not as apparent with the mixture, as the Neshaminy may have clung to some of the sand and reduced water tension of the sand to the filter housing.

Neshaminy soil tended to clog the filters for large volume CERGRENE samples. For this reason, 250 mL aliquots were obtained of Neshaminy CERGRENE samples from beakers with magnetic stirrers, and these aliquots were analyzed for SS. Thus filters were not overloaded for Neshaminy runs (where overloaded is defined by SM 2540 as exceeding 200 mg of residue). The aliquot method could not be used for microsand or mixture runs, as sand particles tended to be more discrete and a representative sample could not be obtained with magnetic stirrers as with the Neshaminy which formed a more colloidal mixture. Sample loading for the filters exceeded 200 mg for the CERGRENE columns. Thus the larger sand and mixture samples tended to overload the filters, which may have introduced considerable error in microsand CERGRENE runs.

Mixing Basin - Recycle

Three "recycle" samples were obtained immediately prior to filling the Long column. The known concentration in the mixing basin was 300 mg/L, so recycle concentrations should have centered around that number. The recycle concentration of each test was used as the t_0 of the Long column in lieu of averaging the initial measurements at each port in the Long column. The recycle samples were taken from the same pump that filled the Long column. The recycle concentration was thought to better represent the concentration delivered to the Long column. The average recycle concentration for all 15 test was 272 which represented less than a 10% loss overall from the known concentration.

Figure A-6 shows all recycle concentrations for all experiments. The data appear to be spread over a wide range of concentrations, but when viewed by soil type (Figure A-7), it becomes apparent that Neshaminy soil, with its higher percentage of clay and silt, yields tighter distributions around 300 mg/L, while the microsand tends to be much more widely distributed and unpredictable. This is due in part to the nature of the sand particles, which are discrete and dense, and may elude the sampling container or settle beneath the mixer. In addition, the SS analysis was much more robust for Neshaminy than for sand. Thus the mixed soil, with its combination of Neshaminy and sand, shows a distribution not quite as tight as Neshaminy, but not as widely distributed as sand.

Figures A-8 and A-9 show recycle concentrations by order of filling and depth of sampling, respectively. The recycle concentration distribution is closer to 300 mg/L for the experiments where the long column was filled first, and for the experiments where the height above the bottom of the basin was to 35 cm (14 in.) rather than 18 cm (7 in.). A second finding is that filling concentrations are closer to the known concentration when the intake is closer to the surface of the water in the basin. The first finding shows tighter distributions when the long column was filled first, which is probably a result of larger volumes of water providing better mixing. When the CERGRENE columns were filled first, enough water was removed from the basin to interfere with the mixing process. However, an analysis of variance showed no significant difference in recycle concentrations between media type, order of filling or intake depth.

Settleable Solids

The gravimetric settleable solids analysis (SM 2540F) entails first performing a SS analysis on a representative sample. In this experiment, settleable solids samples were taken the same way the Recycle samples were taken.

Figure A-10 shows the non-settleable solids concentration for this method for Neshaminy and mixture media. The settleable solids method was not performed on the microsand as insignificant concentrations of non-settleable solids were expected. The concentrations of the mixture medium is about half that of the Neshaminy, which is expected as the mixture contains half the mass of Neshaminy soils. An interesting result, however, is the tighter distribution of the mixture results, possibly due to a flocculent effect, where charged clay particles may cling to microsand particles and settle more predictably.

Laboratory Experiments 1-15

Concentration versus Time

Figures B-1 through B-30 show plots of the raw data for the long and CERGRENE columns for the 15 experiments. The first nine CERGRENE graphs are shown for completeness only. As mentioned previously, the inconsistency between CERGRENE columns makes it unadvisable to use the data from the first nine CERGRENE runs. Experiments 10 through 15, where one CERGRENE column was used repeatedly, show an increasing pattern in the graphs, as would be expected.

The graphs of the long column results show the pattern of settling for particles of each type. Note the rapid settling for the sand experiments, where concentrations at all ports quickly tail off to near zero. Neshaminy experiments exhibit a more gradual settling pattern, with the higher ports decreasing gradually, and the lower ports less so, as they receive the settled particles from the higher elevations. The mixed soil type shows an initial rapid settling of the sand particles, followed by the more gradual Neshaminy pattern. This becomes even more apparent in Figure B-31, which shows the results of the fifteen experiments on the Long column, averaged by soil type.

Long Column Shortcomings - Initial Concentration Gradient

An inherent problem in the design of the Long column is the lack of reliable uniformity in initial concentration (C_0). The height and volume of the column makes it difficult to deliver the sample quickly enough to ensure minimal settling of solids during the delivery time. Thus, depending on the density and particle size in the sample being delivered, a concentration gradient appears in the time zero measurements. This is compounded by the fact that simultaneous t_0 measurements were impossible to achieve in the Long column by hand (three peolple were perfoming the sampling). Because of the very nature of the sampling methodology, a lag will develop between completion of sample delivery and initial measurements, and between the port measurements themselves. A full minute may elapse between end-of-delivery and first sampling at port 8.

Figure B-32 shows port-by-port (represented by height above the column bottom) average concentrations for each soil type and each time interval. For a well mixed column, t_0 measurements should yield a straight line with zero slope, and a y-intercept equal to the recycle concentration. The slope of the t_0 line indicates the severity of the gradient. While the sand shows a severe lack of mixing, due to the size and density of the particles, the Neshaminy soil shows more uniform concentrations and exhibits better mixing. This is because Neshaminy contained clay particles which have lower specific gravities than sand and typically are not spherical in nature. The Neshaminy also took longer to settle with significant concentrations after one hour while the sand had settled out within five minutes. This problem has long been recognized as a shortcoming of the Long column, and causes the scatter that can be seen in the early measurements of more in-depth analysis.

In fact, concentrations for the lower Ports 5, 7 and 8 , especially 7 and 8, during the test using the Neshaminy soil were probably demonstrating hindered zone settling and could even have been displaying compression zone settling. Concentrations were relatively flat throughout the test, except for an initial dip, and even began to exceed the known delivered concentration of 300 mg/L for ports 7 and 8 after one hour as demonstrated in Figure B 31.

CERGRENE Shortcomings - Lack of Repeatable Results

The precision of the SS concentration in the mixing basin can be calculated from the analysis of triplicate samples. The precision of the CERGRENE columns can be calculated from the duplication of a sample at a specified time.

Precision for duplicate analysis was estimated by calculation of the relative percent difference using the following equation:

$$RPD = ((C_1 - C_2) \times 100) / ((C_1 + C_2)/2) \quad (3\text{-}3)$$

where RPD = relative percent difference
C_1 = the larger of the two observed values
C_2 = the smaller of the two observed values

When three or more replicates are available, the relative standard deviation (RSD), instead of the RPD, was used as follows:

$$RSD = (s/y)x100\% \quad (3\text{-}4)$$

where: s = standard deviation, and
y = mean replicate analysis.

The standard deviation is defined by:

$$s = \sqrt{\sum_{i=1}^{n} \frac{(y_i - \bar{y})^2}{n - 1}} \qquad (3\text{-}5)$$

where: s = standard deviation
y_i = measured value of the *i*th replicate
y = mean of replicate measurements
n = number of replicates

For each run, a duplicate CERGRENE column was tested and three Recycles were taken The differences in these values is presented in Table 3.3.

Table 3.3 Duplicate Analysis for Recycle Concentration and CERGRENE Columns

Test #	QA Run #	Withdrawal Height (cm)	Filling Sequence	Media	Recycle		CERGRENE Duplicate	
					RPD (%)	RSD (%)	Duplicate Time (min)	RPD (%)
1	8	18	L/C	Neshaminy	- -	0.53	NA	No Duplicate
2	12	36	L/C	Mixture	26.1	- -	3	28.6
3	11	18	C/L	Mixture	- -	14.7	3	18.6
4	3	36	C/L	Neshaminy	- -	24.2	1	7.2
5	5	18	L/C	Neshaminy	- -	6.2	0	23.8
6	14	18	L/C	Microsand	2.6	- -	60	9.8
7	15	36	L/C	Mixture	- -	11.8	10	35
8	1	18	C/L	Microsand	- -	14.1	5	5.9
9	9	36	C/L	Mixture	- -	9.1	3	8.2
10	6	36	L/C	Neshaminy	- -	5.6	1	0.56
11	10	18	L/C	Mixture	- -	8.8	0	0.25
12	13	36	L/C	Microsand	- -	5.3	10	22.2
13	4	18	C/L	Microsand	17.8	- -	5	12.6
14	7	36	C/L	Neshaminy	4.9	- -	60	1.1
15	2	18	C/L	Microsand	- -	9.6	1	2.1

This data indicates that the variation of the recycle concentration for each test was random and not media driven (microsand, Neshaminy and mixture). This may due in part to the

size of the samples taken (about 250 mL) and the force with which the sample bottles were filled by the pump (the same pump used to fill the Long column).

The duplicate analysis for the CERGRENE column tells a different story. During the first nine tests, four CERGRENE columns were used. For the remaining six tests, only one column was used. Here the CERGRENE columns behave randomly for the first nine tests, and then duplicate analysis improves dramatically as distinct patterns can be interpreted from the media being tested. The Neshaminy and mixture have better duplicates than the microsand. While the amount of data may not be large enough to state this finding with statistiscal validity, this observable result is expected. The percent recovery analysis of the "Standard Reference Material" indicated the microsand had the largest variation while the Neshaminy had the least with the mixture somewhere in between. That the performance of the CERGRENE columns in the last six test shows that the duplicate were better than the expected results from the SRM analysis may be due in part to the CERGRENE columns using larger volumes of sample.

As the recycle concentrations continued to behave randomly, the improved CERGRENE performance in the latter test was not due to enhanced technique of the testers as the experiment progressed. One column, instead of a several columns each with their own idiosyncracies, produced repeatable results. This duplicate analysis only compared the SS concentration and not settling rates.

Percent Removal Long Versus CERGRENE

Traditional methods of computing settling velocity distribution based on settling column data rely on a simple depth per time relationship. In the Long column, the depth measurements from each port in the Long column are divided by time of the sample to calculate the settling velocity distribution or the design overflow rate which can then be used in settling tank design. Though this computed number is in units of length per time (cm/s), it is not equivalent to a discrete particle settling velocity. The C_0 in the Long column are presumed to be uniformly distributed at all depths, however no direct measurement can be made to the length of the particles' flow path. Had a plug flow been introduced in the top of the column, the settling velocity computation would be more straightforward.

This design overflow rate was plotted versus the percent removal. For the Long column, percent removal is defined as the SS concentration at the port compared to the average recycle concentration for that run, which is the theoretical C_0 at every port. Though the actual C_0 at each port were obviously not equal to the recycle concentrations (see discussion on lack of well-mixed conditions), this is a necessary assumption to construct a plausible settling curve, and resulted in practical results with little scatter for the slower settling solids.

For the CERGRENE column, the overflow rate is compared to percent removal for each column of time greater than zero. Overflow rate is computed by dividing the distance an average particle traveled by the time measurement of the column. Thus, for each CERGRENE column, the number is computed by dividing one-half of the length of the upper portion of the water column (from the middle ball valve until the top water level) by the specific column's time, be it 1, 3, 5, 10 or 60 minutes. The C_0 in each column is assumed to be equal to the time zero

column's bottom portion concentration. Percent removal is defined to be each column's top portion concentration (computed by comparing to the bottom portion concentration) divided by the column's assumed C_0.

Figures C-1 through C-9 show Long column results for experiments 1 through 9. The CERGRENE results are not reliable and are therefore not shown. Figures C-10 through C-21 show long and CERGRENE results for experiments 10 through 15. The shapes of settling curves are comparable for the two methods, the immediately obvious flaws are apparent in the sand experiments (12, 13, and 15). The Long column is overstating overflow rates for the fast settlers, as the right side of the Long column graphs should approach zero for increasing settling rates, and the CERGRENE columns are under estimate removal rates, as they should approach 100% on the left side of the graphs. For the Long column, this shortcoming is due to the lack of adequate initial mixing. The assumption of C_0 being equivalent to average recycle concentration yields false concentration for the rapid settlers. For the CERGRENE column, the very large volumes of analytes made it difficult to do the SS analysis for sand. Theoretically all the sand should vave settled out at five and ten minutes and percent recovery should have been 100% . Losses of mass result in prediction of lowere concentrations. Besides the problems with the SS anlysis already discussed under *Completeness,* some sand particles may have been trapped in the ball valve mechanism. This is currently under investigation.

Matrix Iteration Process for CERGRENE Columns

The CERGRENE group of France (Lucas-Aiguier et al., 1997) developed a methodology to use the data from the small columns to produce settling velocity distributions. A spreadsheet application, "VICTOR", was developed which utilizes an iterative method to solve simultaneous equations, resulting in a matrix *M(i,j)* which contains mass removed for each particular time interval *i* and pollutant *j*. Based on this matrix, a distribution of settling velocities may be constructed. A more complete description of the derivation is in Appendix G.

The nature of the CERGRENE process sometimes results in certain points being in error. Thus a graph of M(i,j) for a particular pollutant concentration, in our case SS, versus time, which should increase monotonically, may have discrete points which exceed the following temporal point. The software allows the user to choose either analysis of all points, which includes all data in the computation of the velocity distribution, or analysis with "suppression", which excludes points which do not show the expected increasing concentration in time. The choice of suppression or non-suppression is based upon several factors, but unless the points in question are significantly skewed to one direction, it will not have a severe impact on the resultant velocity distribution.

As discussed earlier, further analysis of CERGRENE experiments 1 through 9 is not valid due to the inconsistencies between columns. Figure D-1 illustrates experiment 9, where the column order was randomized, and no consistent pattern can be seen in either graph. Suppression is not possible with this data, as no pattern can be inferred from the mass removal graph. This may be contrasted with Figure D-2, which shows the results from experiment 10, where one column was cleaned and reused for each time interval. Monotonically increasing mass removal values are seen, as well as a more varied velocity distribution.

Figure D-3 shows the results of experiment 11, utilizing all points. Figure D-4 shows the results after suppressing points 2 and 5, which fall outside of the expected pattern. Note the differences in the velocity distributions, especially in the slowest reaches, where the 3600 second point was suppressed. The basic shape of the distribution, however, remains the same.

Figure D-5 shows experiment 12, where suppression was not possible, because suppression would leave only 2 points for analysis. The shape of the velocity distribution, however, is similar to that of experiment 13 (Figure D-6), both of them being sand experiments. The third point in Figure D-6 could have been suppressed, but it does not fall far outside the curve, and thus is probably more useful being left in the analysis. Suppression of this point results in a sharper drop-off at the slower settling velocities.

Figures D-7 through D-10 illustrate experiments 14 and 15, with and without suppression. Note that the shapes of the velocity distributions remain similar whether or not points are suppressed.

VICTOR proves a useful tool for computing a settling velocity distribution for the CERGRENE columns. Care must be taken, however, in trying to compare these velocity results to the results from other types of analysis, which use different assumptions and computational techniques, and even different methods for deriving settling velocity distribution. Additionally, VICTOR would appear to work better with higher numbers of samples and time intervals. The capability of the software to track several pollutants could be a very useful for partitioning experiments, though this feature was not examined here.

Eckenfelder Analysis for Long Column

Use of Eckenfelder plots proved to be an inappropriate analysis for the media in Phase II. The Eckenfelder analysis is generally used to provide flocculent analysis. For the analysis to be successful, iso-concentration lines need to be developed from plotting concentration values for each sample depth (y coordinate) and time (x coordinate). The clay particles were not settling, and in fact concentration increased at the lowest port for several experiments at the one hour mark. This, as stated earlier, seemed typical of hindered or compaction zone settling. During the sand and mixture experiments the sand settled within a five minute time frame and exhibited properties of discrete settling.

Design Removal Comparison

Table 3.4 shows calculated overflow rates versus percent removals for the Long and CERGRENE columns for experiments 10 through 15. Calculations were identical to those used to develop the graphs in Appendix C, except that outlying CERGRENE points were deleted if the Victor algorithm suppressed the points automatically. Results from the Victor analysis were wildly divergent from the calculated results in Table 3.4, possibly due to lack of sufficient data points to effectively utilize the Victor tool. In fact, settling velocity results of Victor runs do not even show a noticeable difference between media. Comparisons of Long to CERGRENE results shows some similarities, though CERGRENE analysis is complicated by the lack of sufficient data points.

The calculated Stoke's Law settling velocities for ideally spherical sand at 15 °C ranged from 0.5 cm/s for 80 µm diameter sand to 12.6 cm/s for 400 µm. At 230 µm, the d_{50} value as calculated by the Coulter® LS Particle Analyzer for the microsand, the settling velocity was 9.3 cm/s.

Table 3.4 Comparison Predicted Removal between Long and CERGRENE Columns

Experiment (Media)	Percent Removed (%)	Overflow Rate (cm/s) Long†	r^2	Overflow Rate (cm/s) CERGRENE‡	r^2 (#pts)
10 (Neshaminy)	30	0.069	0.81	0.072	0.96 (5)
	50	0.0077		0.010	
	70	0.00086		0.0015	
11 (Mixture)	30	4.4	0.61	0.30	0.99 (3)
	50	0.14		0.0014	
	70	0.0046		0.0000069	
12 (Microsand)	30	100	0.64	100	0.22 (4)
	50	18		1.27	
	70	3.1		0.016	
13 (Microsand)	30	120	0.65	1.8	0.92 (4)
	50	20.		0.076	
	70	3.4		0.0032	
14 (Neshaminy)	30	0.014	0.43	0.61	0.82 (4)
	50	0.00059		0.094	
	70	0.000024		0.015	
15 (Microsand)	30	220	0.66	31000	0.90 (3)
	50	30.		30.	
	70	4.0		0.00028	

† Based on average recycle concentration. Points with calculated %Removal<0 were deleted.
‡ Points removed by the Victor "suppression" algorithm were deleted, often yielding few points. Number of points used in the analysis is shown with the correlation coefficient.

4. Conclusions and Recommendations

The Preliminary Results (Phase I) determined the expected homogeneity of the mixing basins and the initial performance of the respective columns. This testing showed that adequate mixing was provided in the mixing basin, that SS were transferred to the settling columns for further testing, and that the microsand and Neshaminy clay particles were recoverable in the columns. Other materials were tested, e.g., glass beads, but were found to be unsuitable. The Long column had insufficient head to sample from the top two ports. Only ports 3, 5, 7 and 8 were used during the evaluation for determination of settling methods. At this point analysis had been performed independently by the EPA and John Meunier, Inc.

The objective of the Phase II experiments was to compare, in side-by-side analysis, two methods of measuring settling velocity. Lab study results indicated that the CERGRENE columns have some advantages, such as ease of use, smaller testing volumes and a consistent initial concentration, but also significant problems such as loss of SS mass and lack of reproducibility for other time measurements. The Long column had its own advantages, such as repeatability and consistent (predictable) SS removals, while the disadvantages included poor initial concentration measurement, large testing volumes and large number of SS analyses required.

Phase II experiments were also designed to determine the optimal withdrawal point in the mixing basin as well as the effect of filling order on experimental results and will be used in Phase III.

The original experimental design did not account for the three most important factors affecting results during the Phase II of the experiment:
1. Individual behavior of the CERGRENE columns
2. Overloading of the filter by the samples
3. Wide variation in SS concentrations in the attempt to capture the micro-sand

Initial conclusions from Phase II are:

1. Microsand was more difficult to work with than anticipated. It was difficult to recover all of the microsand during SS analysis. This is a result of the physical characteristics of the sand, as particles tend to stick to analytical equipment and loss of mass easily occurs. This loss was especially noticeable in the CERGRENE samples where the large volume of analyte caused the filters to become overloaded. The microsand was a major source of error to the experiment; however this error had a distinct bias as the analysis of the "standard reference material" was in the direction of a loss of sand.
2. The performance of the CERGRENE columns was erratic for experiments 1-9. While the expected results of a plot of concentration versus time would be an increase in the concentration with time, the columns in experiment 1-9 behaved almost randomly. In contrast, experiments 10-15, where only one column was used, indicated a trend of

increasing concentration versus time. This seemed to point to a lack of consistency between columns.

3. The long column was never fully mixed at t_0, especially for the microsand and mixture test.
4. The CERGRENE columns were examined for defects and sizing specifications for volumes and height. No anomalies were found, though a small indentation in the ball valve could be trapping some solids and releasing them later.

Recommendations for the CERGRENE column are:

1. CERGRENE Columns should be modified to allow filling to a constant head (which has already been adapted by the CERGRENE research group in France). The water height in the column is an essential measurement for this test. Starting at the same height would also allow for better duplicate analysis.
2. The filling procedure should allow at least a ½ volume overflow to purge the lines.
3. More data points should be evaluated . The matrix analysis spreadsheet "Victor" currently allows for nine data points not including the initial time and final time.
4. Aqueous volumes should be reduced for SS analysis. This could be accomplished by reducing the volume of the bottom portion of the column and/or splitting samples to avoid overloading.
5. Evaluations of other types of valves should be conducted to attempt to minimize interference of the valve mechanism on solids settling.
6. A mass balance should be performed around the center ball valve. The concentration of the top and bottom parts of the column should be measured at t_0, to ensure that the initial concentrations, before settling, are the same.

Long column recommendations are:

1. The long column should be retrofitted with a device that allows an overflow to achieve better mixing and to allow for a repeatable starting depth.
2. A more powerful pump and mixer should be employed to reduce the concentration gradient of SS in the column at time zero.
3. Delivery of a well mixed plug flow at the top of the column would allow for easier computation of settling velocity. This method should be further investigated.

General recommendations:

In future experiments using the microsand, the time of samples should be reduced to five minutes while increasing the frequency samples. As previously discussed, the microsand diameters are larger than originally reported which increases the settling rate.

It was a benefit from our standpoint to analyze "standards" using the same media that was used in the experiments. This data confirmed that we should expect large error (or losses) for the media in the course of the SS analysis. However, for the sake of confirming the SS analysis technique, diatomaceous silica should have been used for standard reference material. In addition, the same sample bottle sizes should have been used for the standard volumes as the experimental samples.

5. REFERENCES

Aiguier, E., G. Chebbo, J. L. Bertrand-Krajewski, P. Hedges, and J. N. Tyack. "Methods for Determining the Settling Velocity Profiles of Solids in Storm Sewage." Proceedings of IAWQ/IAHR's *International Conference on Sewer Solids - Characteristics, Movement, Effects and Control*, University of Abertay Dundee, Scotland, 1995.

Camp, T. R. "Sedimentation and the Design of Settling Tanks." In *Proceedings American Society of Civil Engineers*, Paper No. 2285, p. 895 - 958 April, 1945.

Chadirat, S., E.Quouillot, J. Tradwell, E. Lucas-Aiguier, and G. Chebbo. *Mise au point d'un protocole de mesure de la répartition de la pollution par classes de vitesses de chute des solides en suspension dans les effluents urbains de temps sec et de temps de pluie.* Centre d'Enseignement et de Recherche pour la Gestion des Ressources Naturelles et de l'Environnement (CERGRENE), France, 1997.

Champigny, M., B. Gagné, M.. Couture and J. Cigana. *Assessment of Known Practices: Sampling Methods*. Internal report for John Meunier, Inc., Montreal, Quebec, Canada, 1997.

Chebbo, G., P. Musquere, V. Milisie and A. Bahoc. Characterization of Solids Transferred into Sewer Trunks During Wet Weather. *Water Science Technology*, 22, (10/11): 231-238 (1990).

Chebbo, G., A. Bachoc, D. Laplace, and B. Leguennec. The Transfer of Solids in Combined Sewer Networks. *Water Science and Technology*, 31 (7): 95-105 (1995).

Dalrymple, R,.J., S. L. Hodd, and D. C. Morin. *Physical and Settling Characteristics of Particulates in Storm and Sanitary Wastewaters*, EPA-670/2-75-011 (NTIS PB 242 001), Cincinnati, OH - Edison, NJ: U.S. Environmental Protection Agency, 1975.

Dickey, D. S. and R.R. Hemrajani. Recipes for Fluid Mixing. *Journal of Chemical Engineering*, **March 1992**, pp. 82-89 (1992).

EPA. *Combined Sewer Overflows - Guidance for Nine Minimum Controls*, EPA 832-B-95-003, Washington, D.C. : U.S. Environmental Protection Agency, 1995.

EPA. *Combined Sewer Overflows - Guidance for Long-Term Control*, EPA 832-B-95-002, Washington, D.C. : U.S. Environmental Protection Agency, 1995.

Eckenfelder, W. W., Jr. "Sedimentation" in *Industrial Water Pollution Control*. McGraw-Hill Book Company, 1966, 28-51.

Etchells, A.W., R.R. Hemrajani, D.J. Koestler, and E.L. Paul. The many faces of mixing. *Journal of Chemical Engineering*., pp. 92-94, March 1992.

Fischer, D. "Vapor Transport of TCE from Ground Water into Residence Basements: Model Experiments", PhD Dissertation, Rutgers University, New Brunswick, NJ, October, 1995.

Gagné, B. and J. Bordeleau (1996). “Vitesse de chute des particules Essais Comparatifs des méthodes allemande et américaine”, Fevrier 1996, CEGEO, pp 46.

Lager, J. A., W. G. Smith, W. G. Lynard, R. M. Finn, and E. J. Finnemore. *Urban Stormwater Management and Technology: Update and Users’Guide.* EPA-600/8-77-014 (NTIS PB 275-654), U.S. Environmental Protection Agency, Edison, NJ, 1977.

Lucas-Aiguier, E., J. Bertrand-Krajewski, and G. Chebbo (1997). “Protocole Victor de Mesure de la Distribution des Polluants en Fonction des Vitesses de Chute dans Les Effluents Urbans” CERGRENE, Agence de l’Eau Seine Normandie *(In French)*.

Lygren, E. and T. Damhaug (1986). "The Swirl Concentrator as an Urban Runoff Treatment Device", In *Proceedings of the NATO Advanced Research Workshop on “Urban Runoff Pollution.”* August 26-30 1985 Montpeliier, France, pp.713 - 724. Ed. by H. C. Torno et. al., Springer-Verlag Berlin Heidelberg.

Michelbach, S. and C. Wöhrle. Settleable Solids in a Combined Sewer System, Settling Characteristics, Heavy Metals, Efficiency of Storm Water Tanks, *Water Science Technology*. 27, (5-6):153 - 164 (1993).

Pisano, W.C., and Brombach, H. “Solids Settling Curves: Wastewater solids data can aid design of urban runoff controls.” *Water Environment Technology* 8 (4):27-33, (1996).

Pisano, W.C., Connick, D. J., and Aronson, G. L. *Swirl and Helical Bend Regulator/ Concentrator for Storm and Combined Sewer Overflow Control*. EPA-600/2-84/151 (NTIS PB 85-102 523), Cincinnati OH - Edison, NJ: U.S. Environmental Protection Agency, 1984.

Standard Methods for the Examination of Water and Wastewater (1995). Edited by A. D. Eaton, L. S. Clesceri, and A. E. Greenburg. Published Jointly by American Public Health Association, American Water Works Association and Water Environment Federation, 19th Edition.

Tchobanoglous, G. and Burton, F. “Physical Unit Operations” In *Wastewater Engineering: Treatment, Disposal and Reuse.* Metcalf & Eddy, Inc. - 3rd Edition McGraw-Hill, Inc. 1991, 193 -300.

Tyack, J. N., P. D. Hedges, and R. P. M. Smisson “A Device for determining the Settling Velocity Grading of Storm Sewage.” In *Proceedings Sixth International Conference on Urban Storm Drainage*, Volume II pp 1805-1811 Niagra Falls, Ontario, Canada, September 12-17, 1993.

Walker, D., Golden, J., Bingham, D. and Driscoll, E. *Manual: Combined Sewer Overflow Control*. EPA/625/R-93/007 (NTIS PB 93-144 649), Cincinnati, OH: U.S. Environmental Protection Agency, 1993.

Appendix A

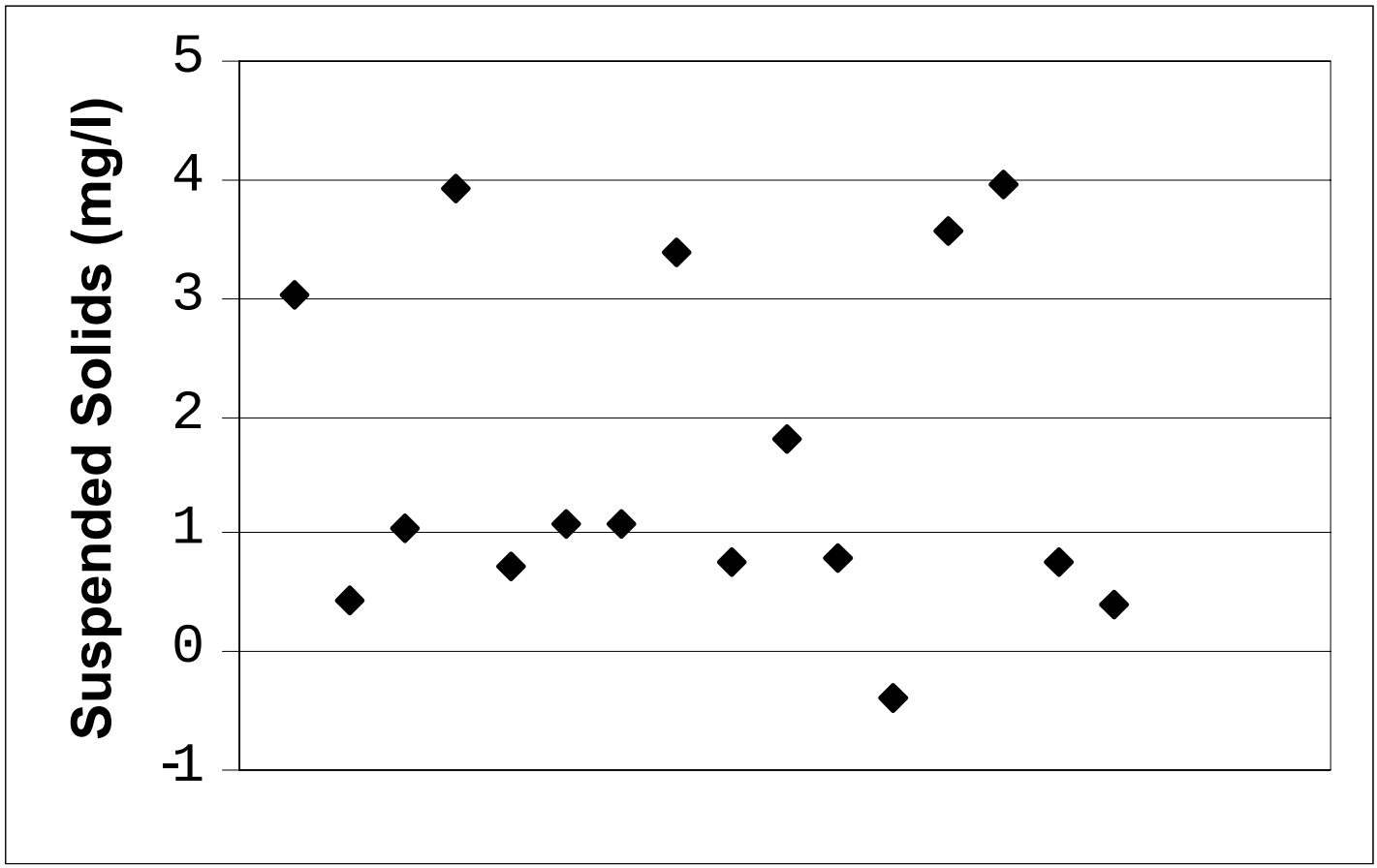


Figure A-1: Concentrations of Method Blanks

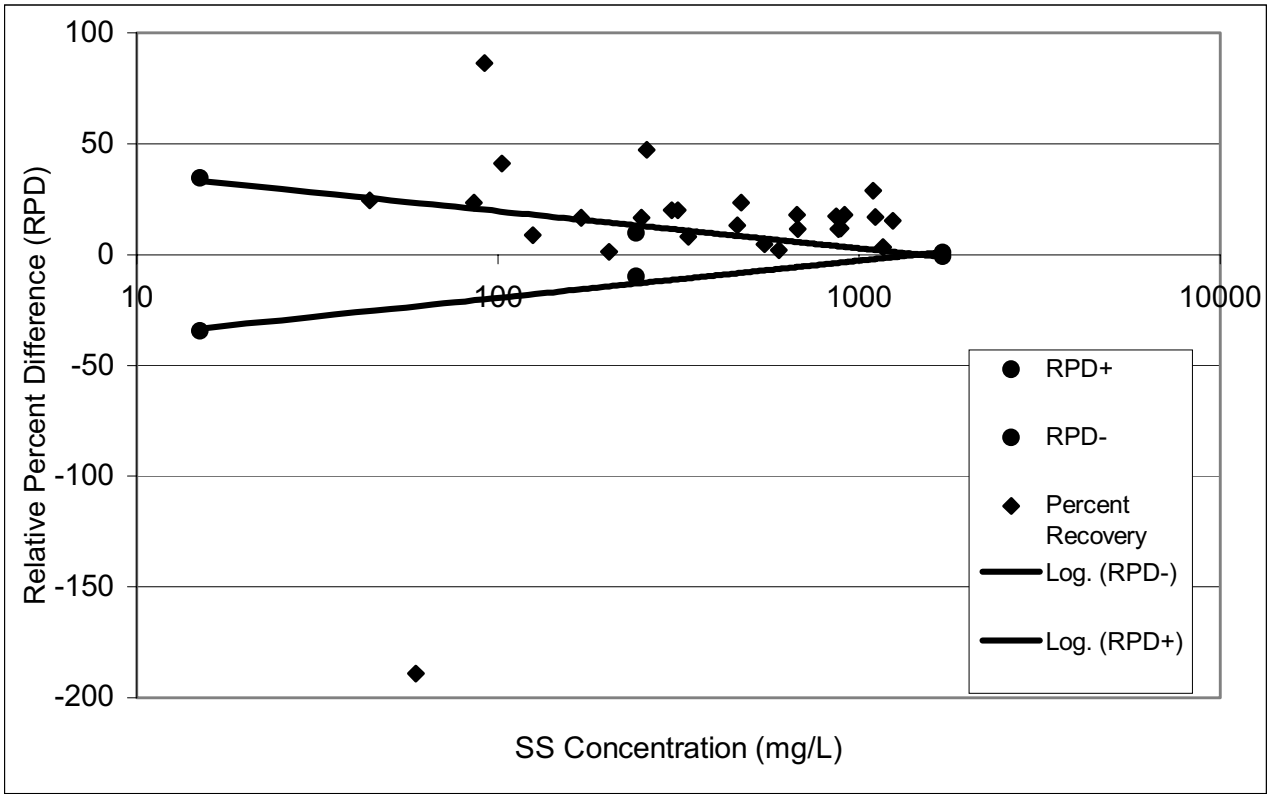


Figure A-2: Relative Percent Difference for Standard Reference Materials

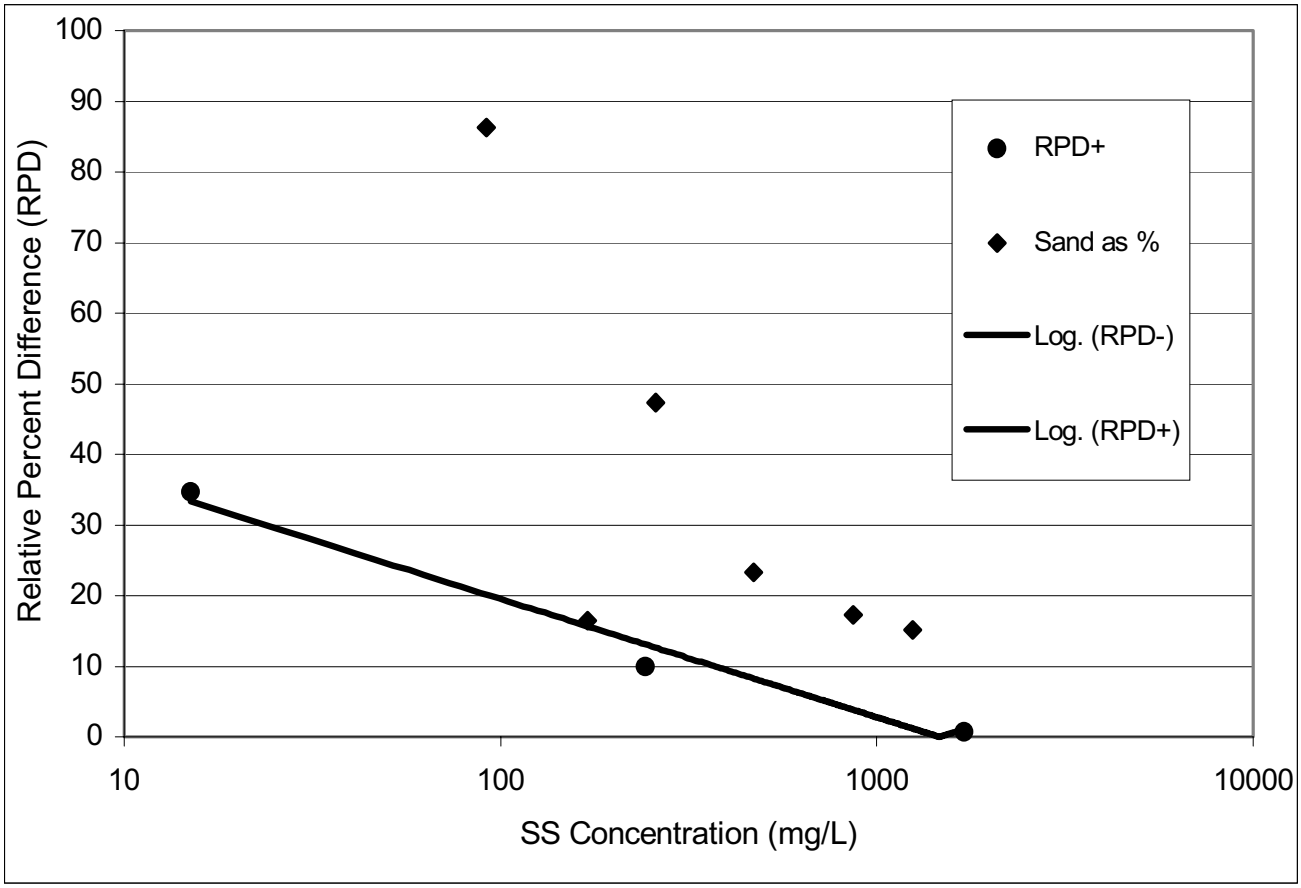


Figure A-3: Relative Percent Difference, SAND

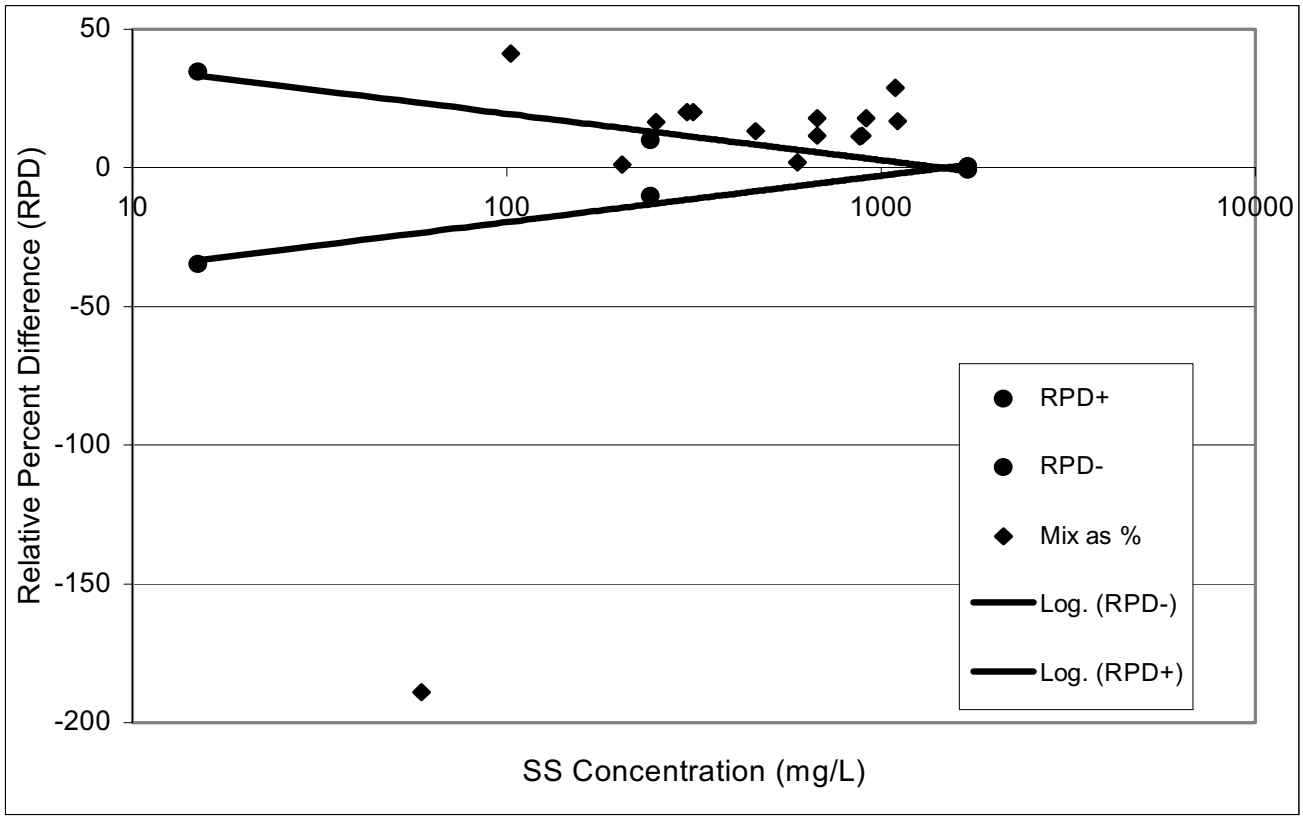


Figure A-4: Relative Percent Difference , MIX

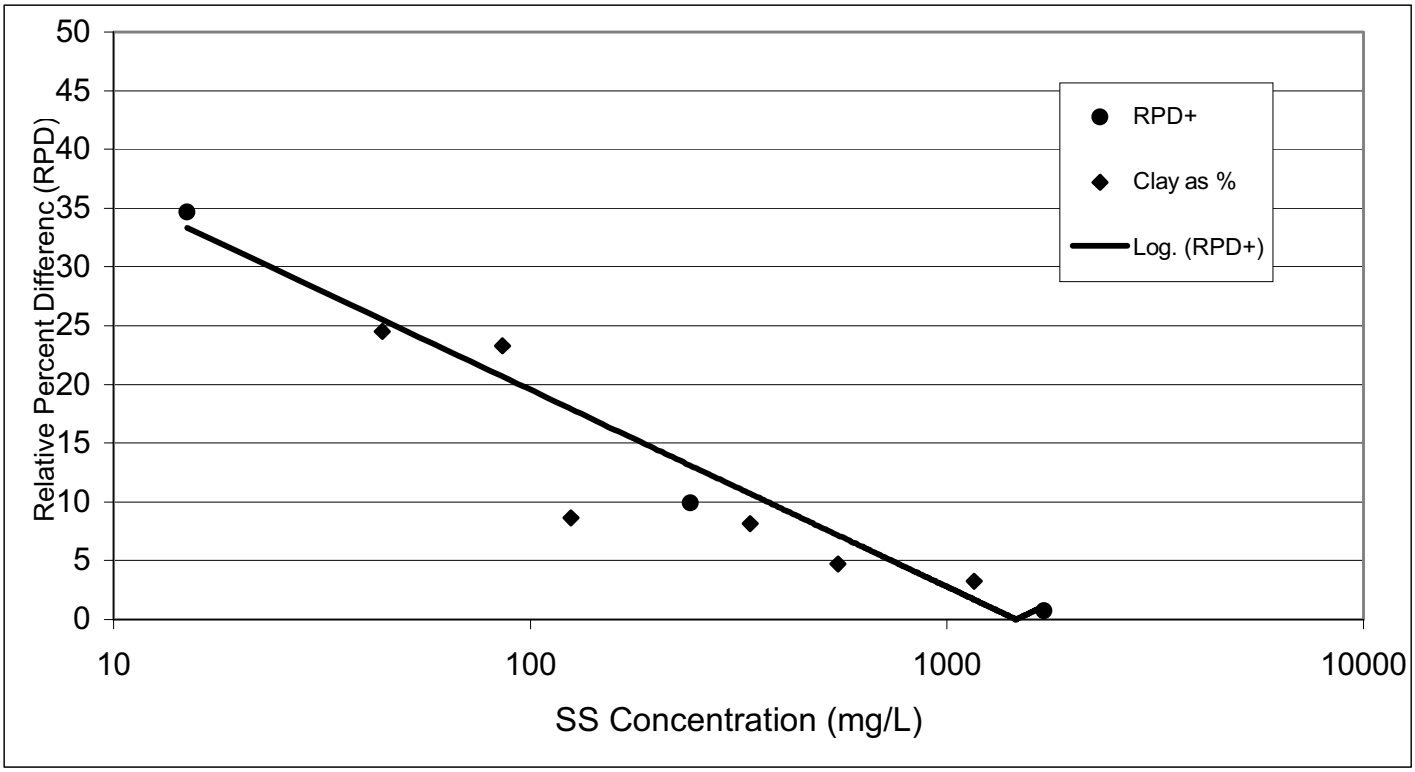


Figure A-5: Relative Percent Difference, NESH

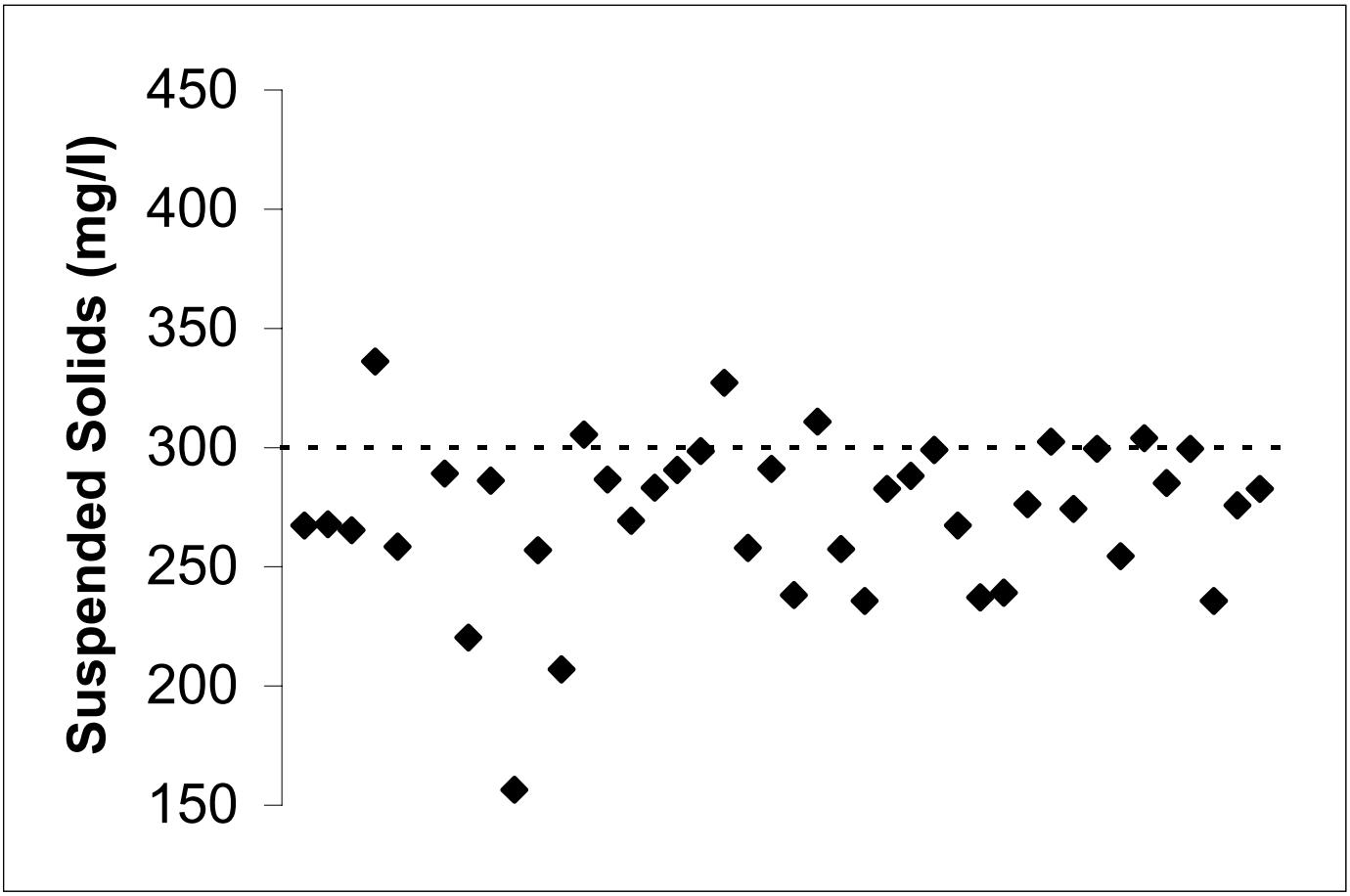


Figure A-6: Recycle Concentration, All Experiments

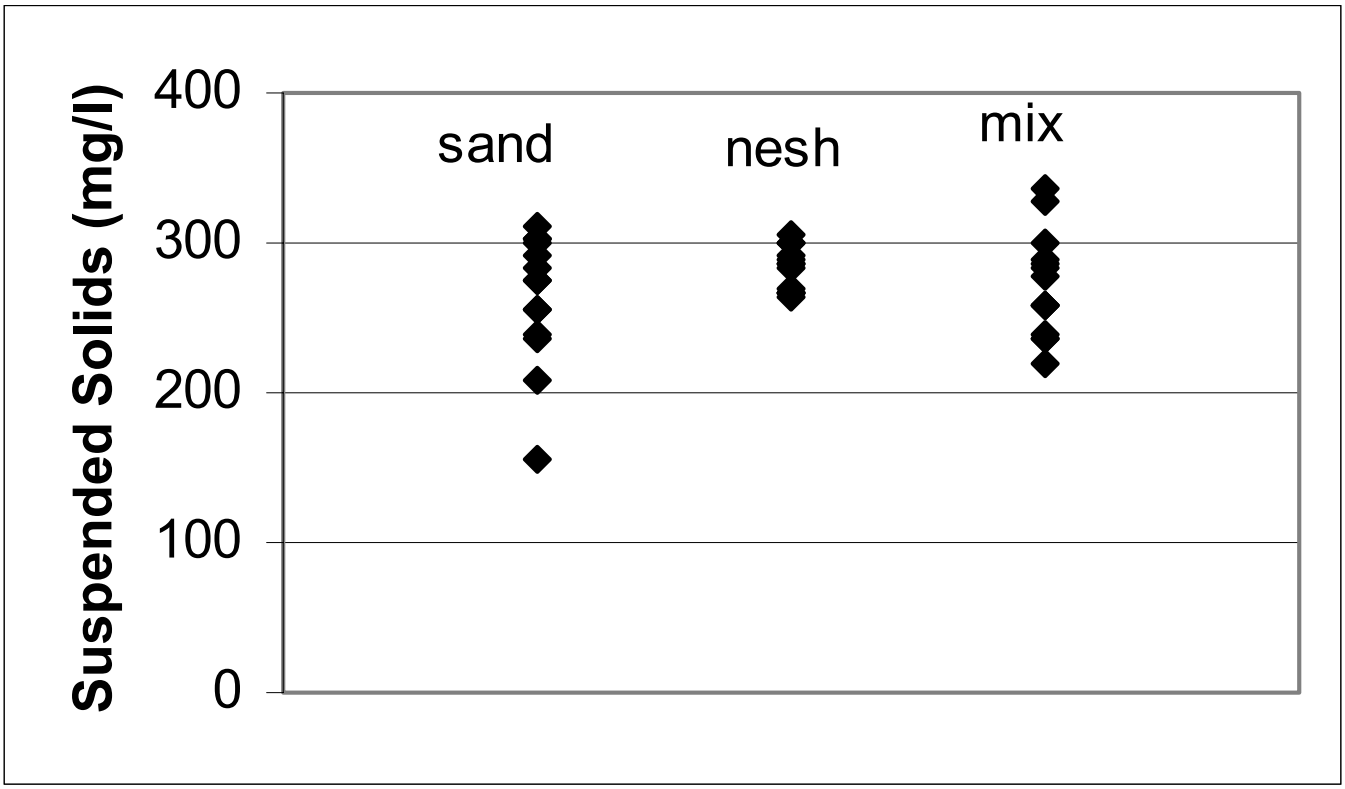


Figure A-7: Recycle Concentration by Soil Type

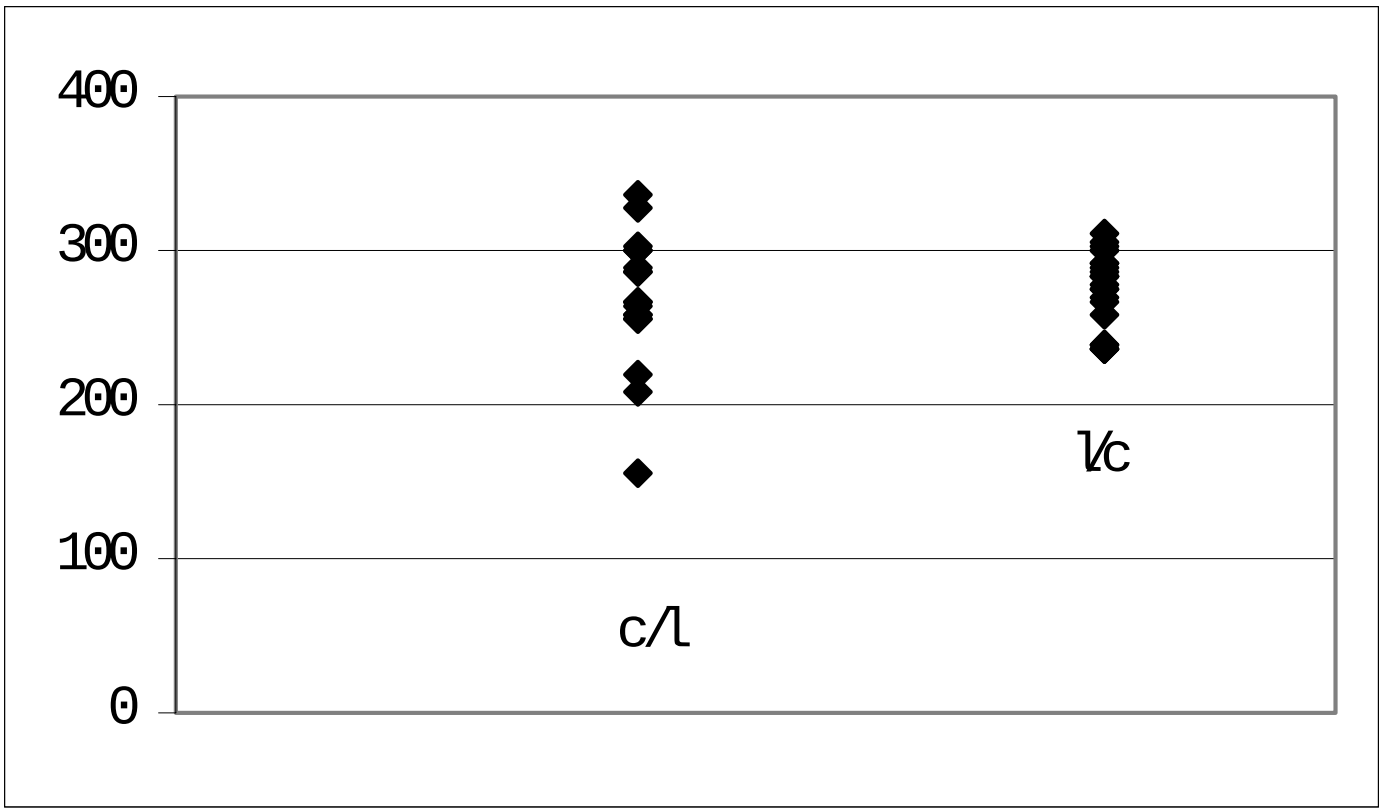


Figure A-8: Recycle Concentration (mg/l), by Order of Filling (c/l=Cergrene-Long, l/c=Long-Cergrene)

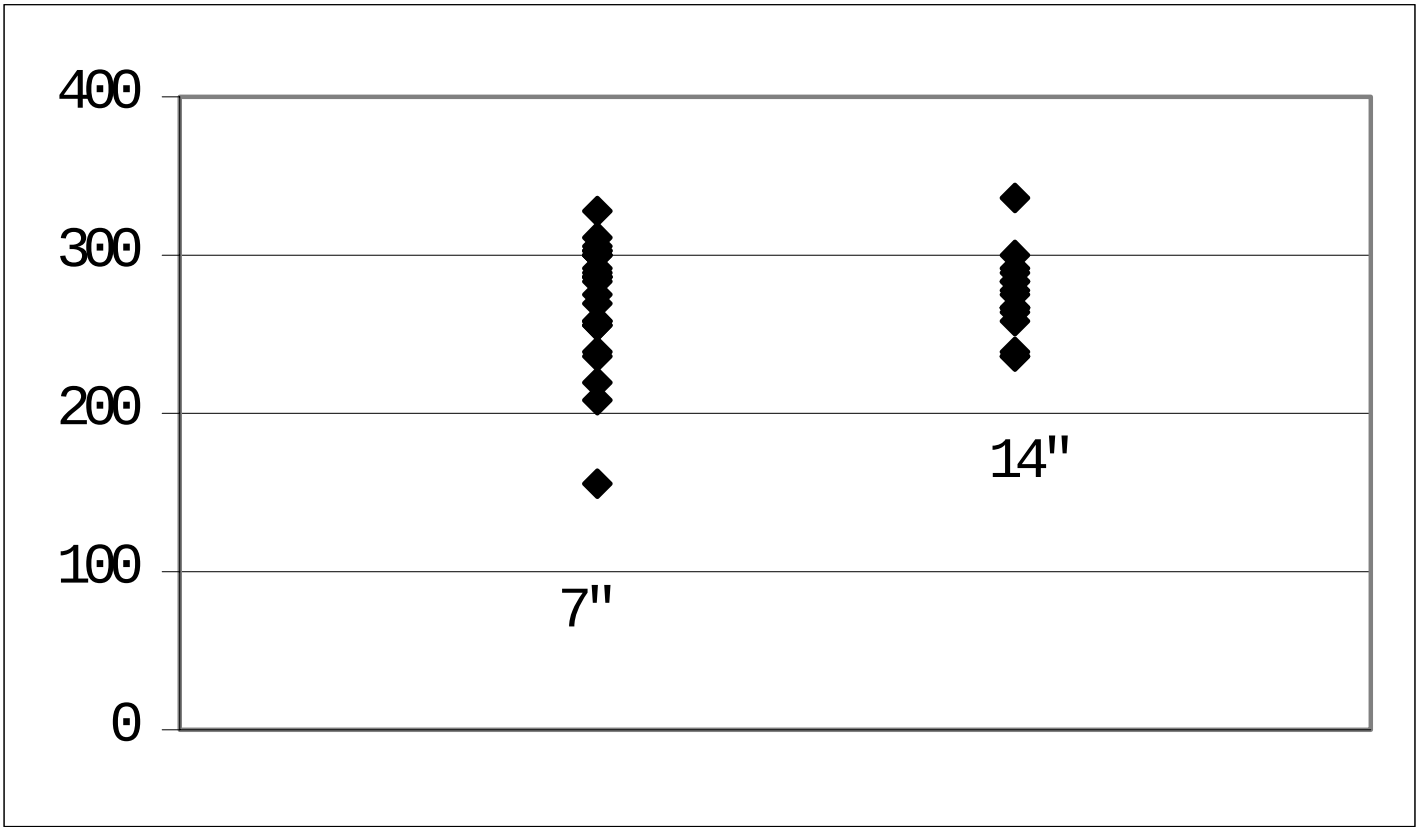


Figure A-9: Recycle Concentration by Intake Depth (height above bottom of basin)

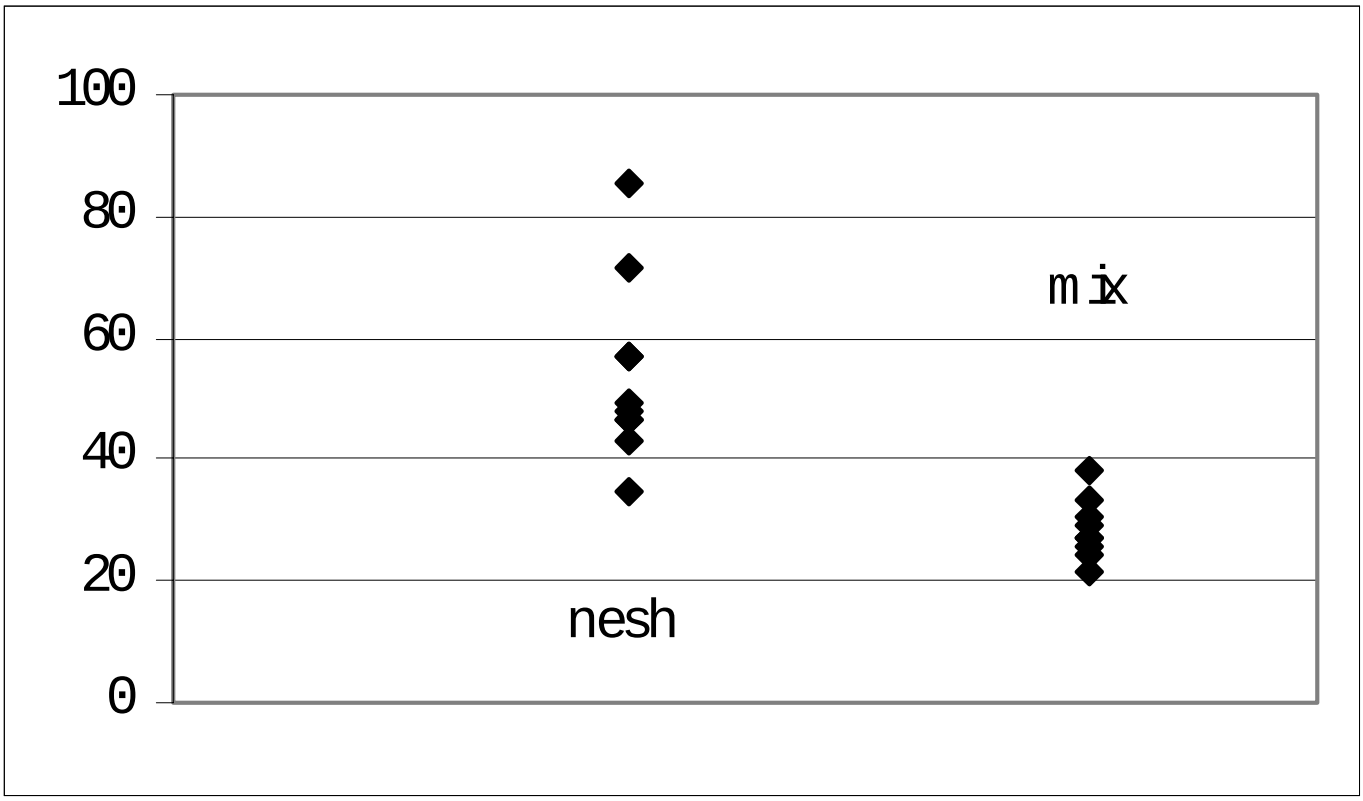


Figure A-10: Concentration in Standard Methods Graduated Cylinder after 60 Minutes of Settling, by Soil Type

Appendix B

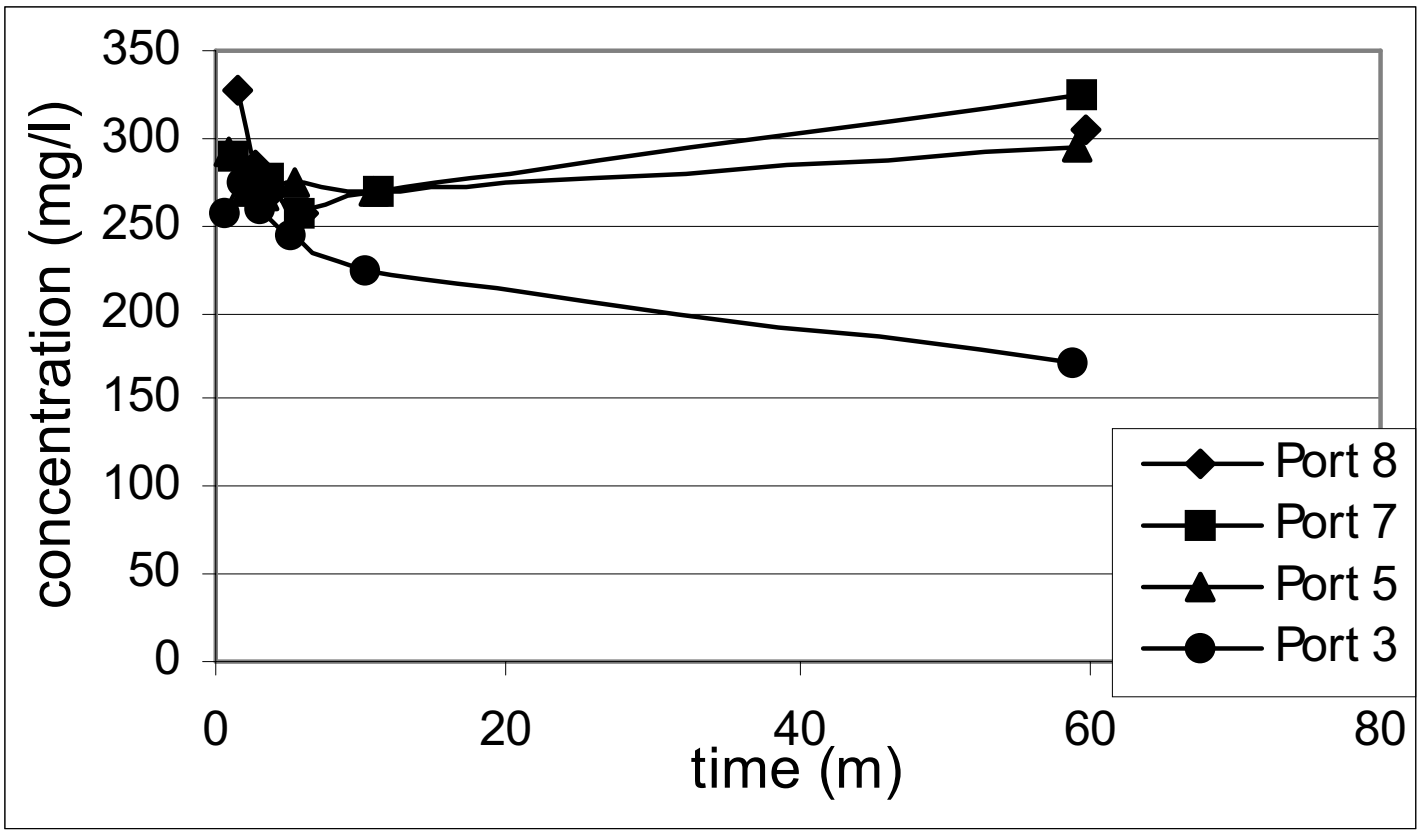


Figure B-1: Experiment 1, Long Column [Withdrawal height 36 cm, filling sequence C/L, media Neshaminy]*

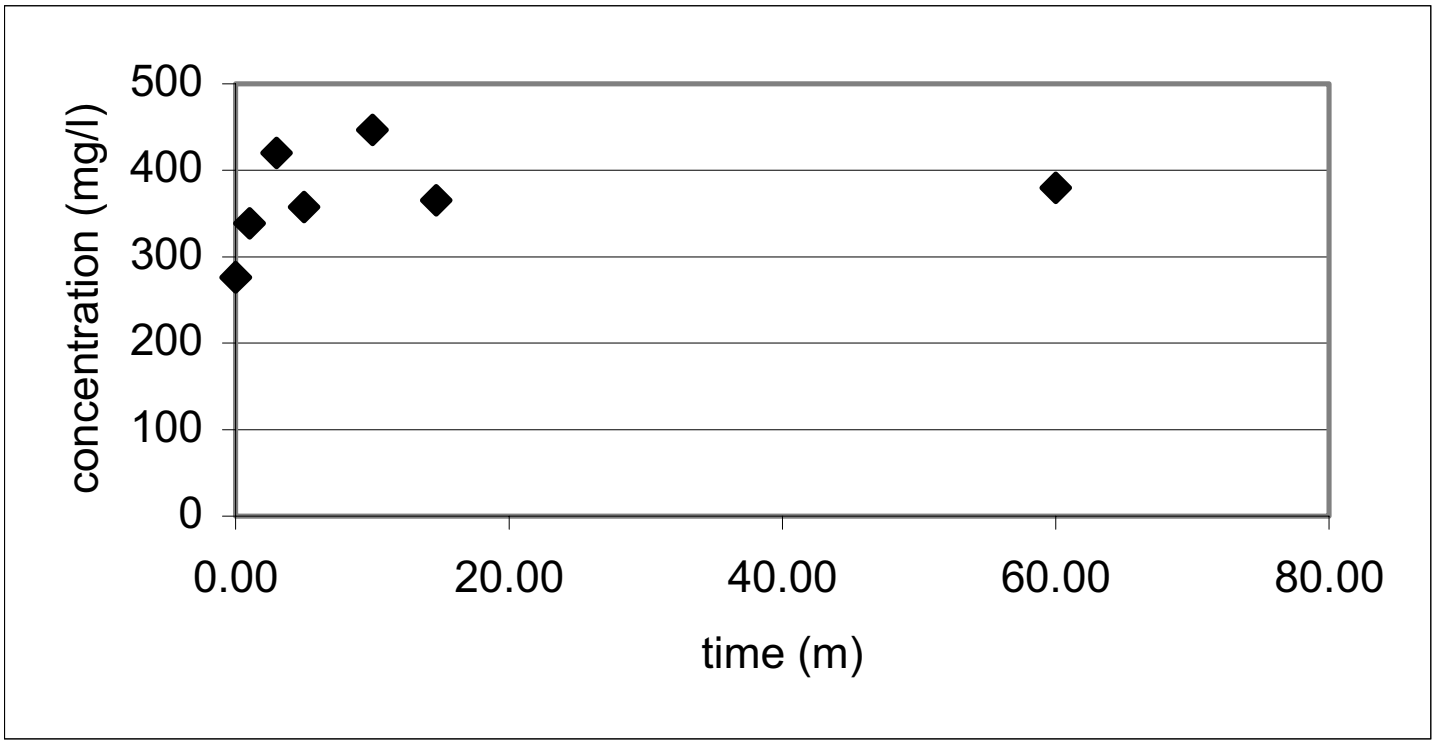


Figure B-2: Experiment 1, CERGRENE (multiple columns) [36 cm, C/L, Neshaminy]

* Experimental parameters in brackets, refer to Table 3.3

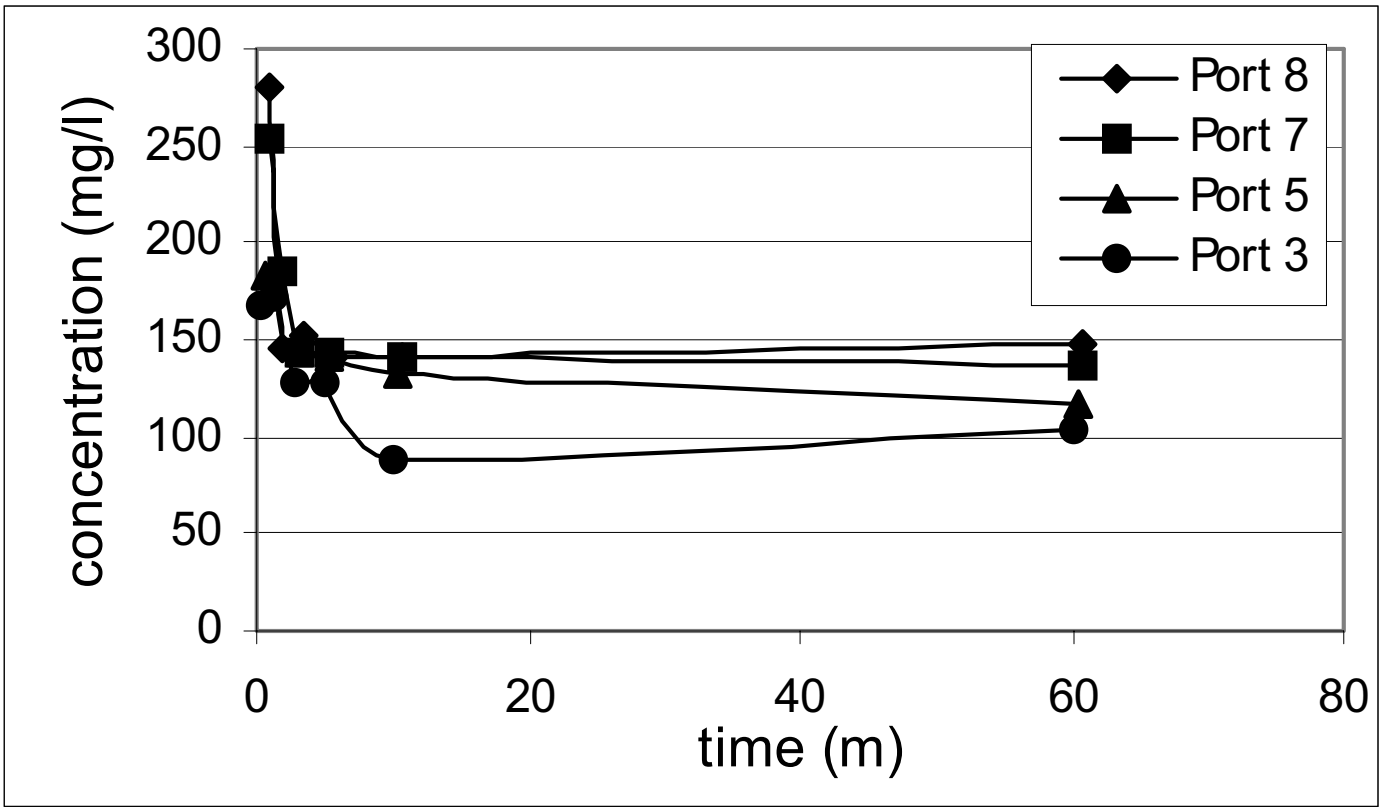


Figure B-3: Experiment 2, Long Column [36 cm, C/L, Mixture]

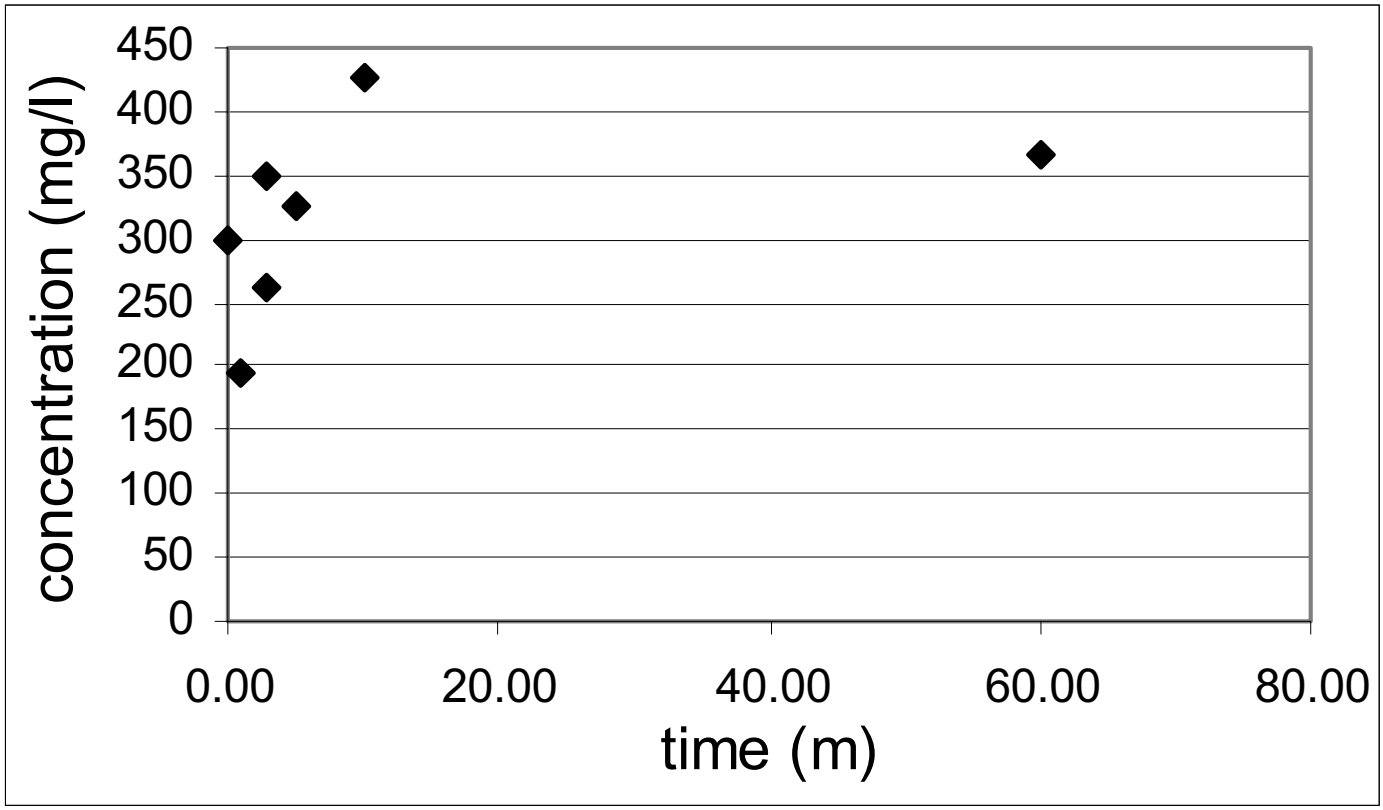


Figure B-4: Experiment 2, CERGRENE (multiple columns) [36 cm, C/L, Mixture]

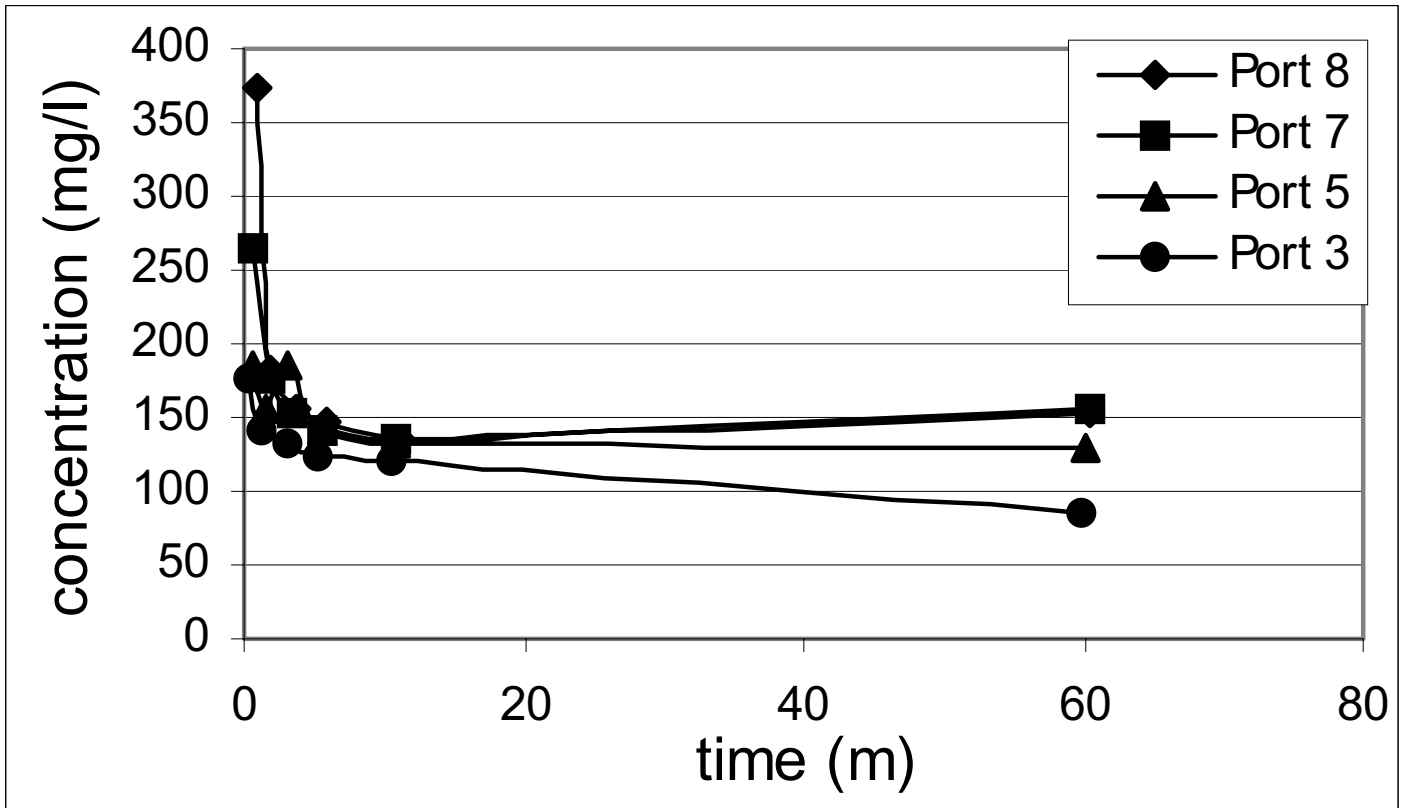


Figure B-5: Experiment 3, Long Column [18 cm, C/L Mixture]

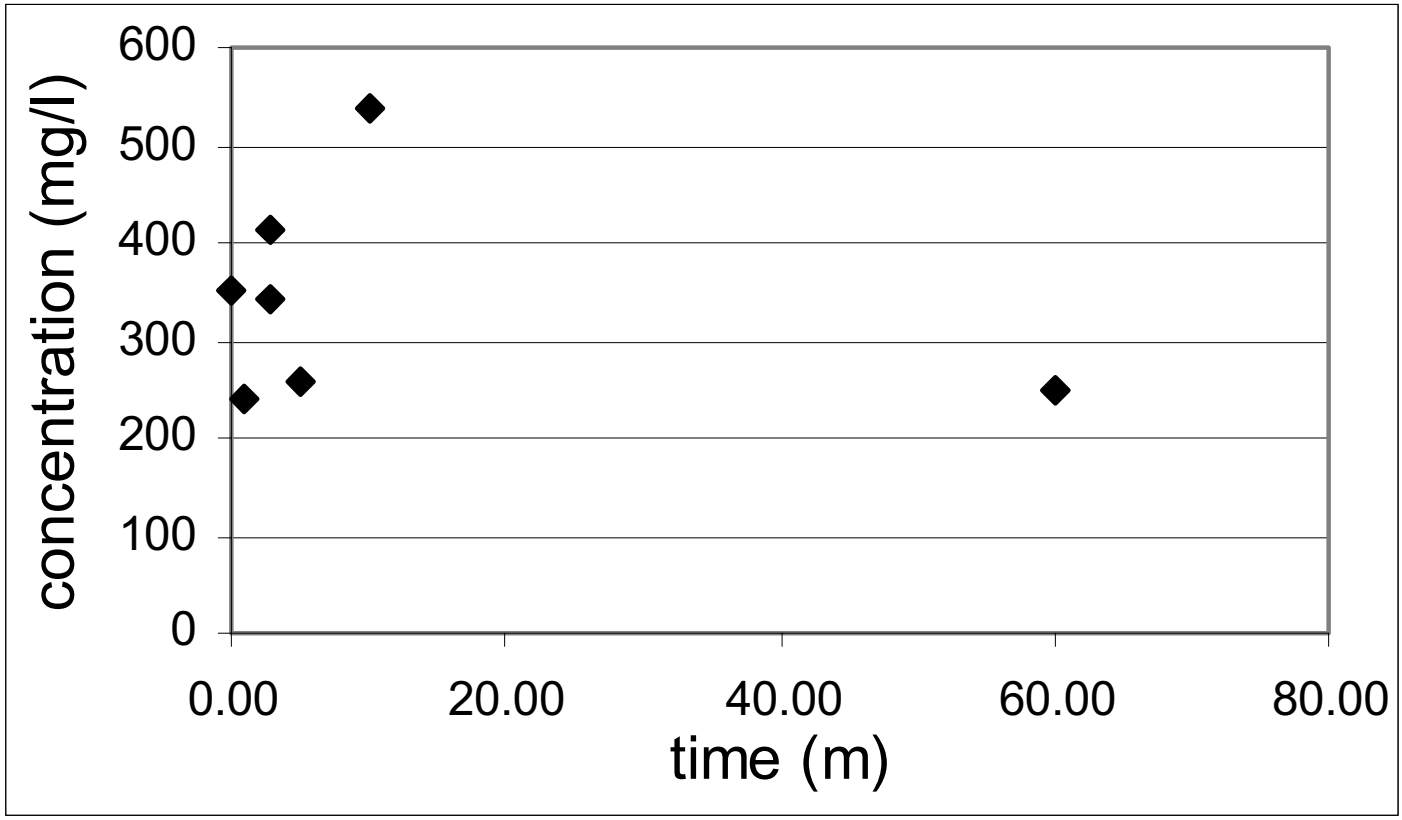


Figure B-6: Experiment 3, CERGRENE (multiple columns) [18 cm, C/L Mixture]

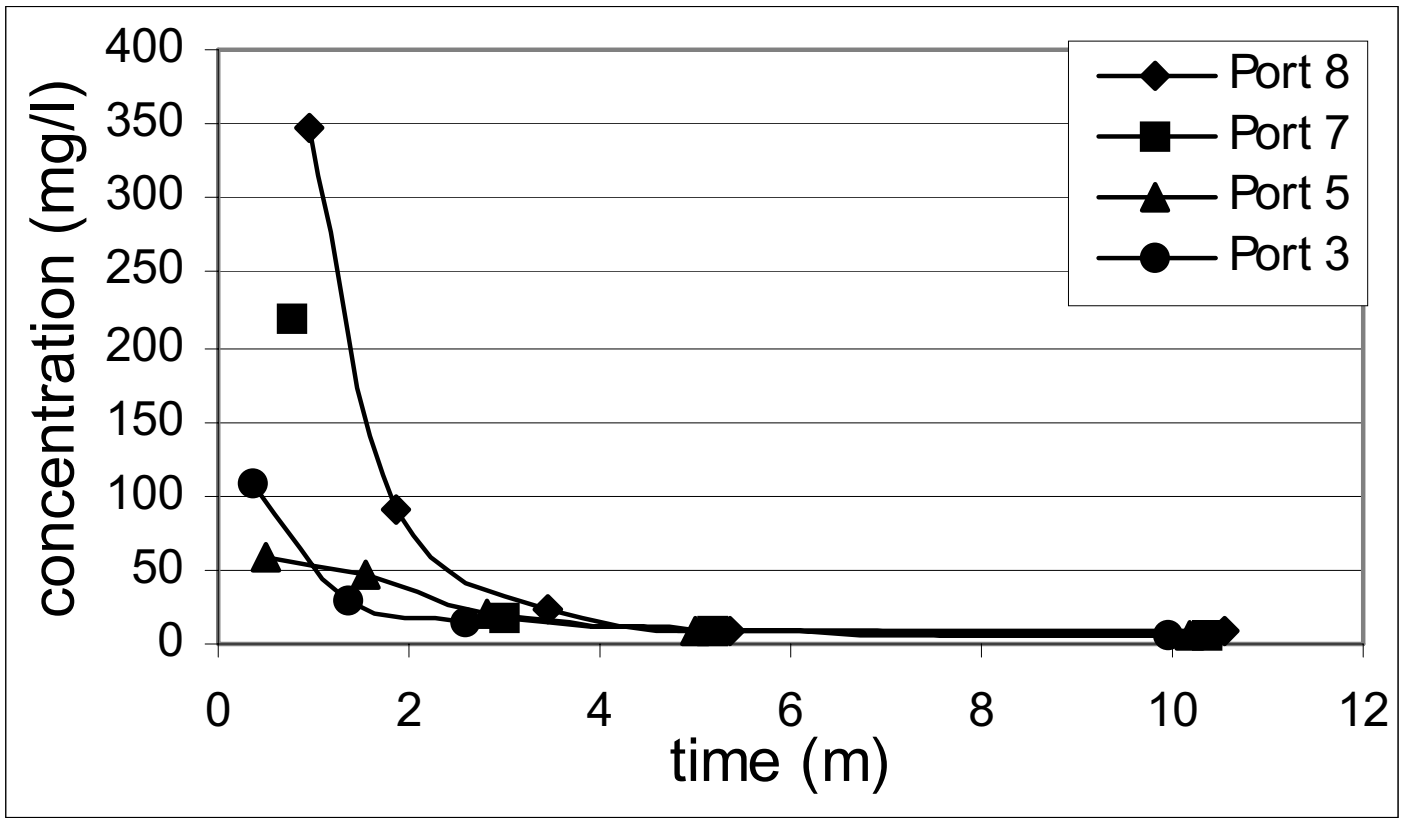


Figure B-7: Experiment 4, Long Column [18 cm, C/L, Microsand]

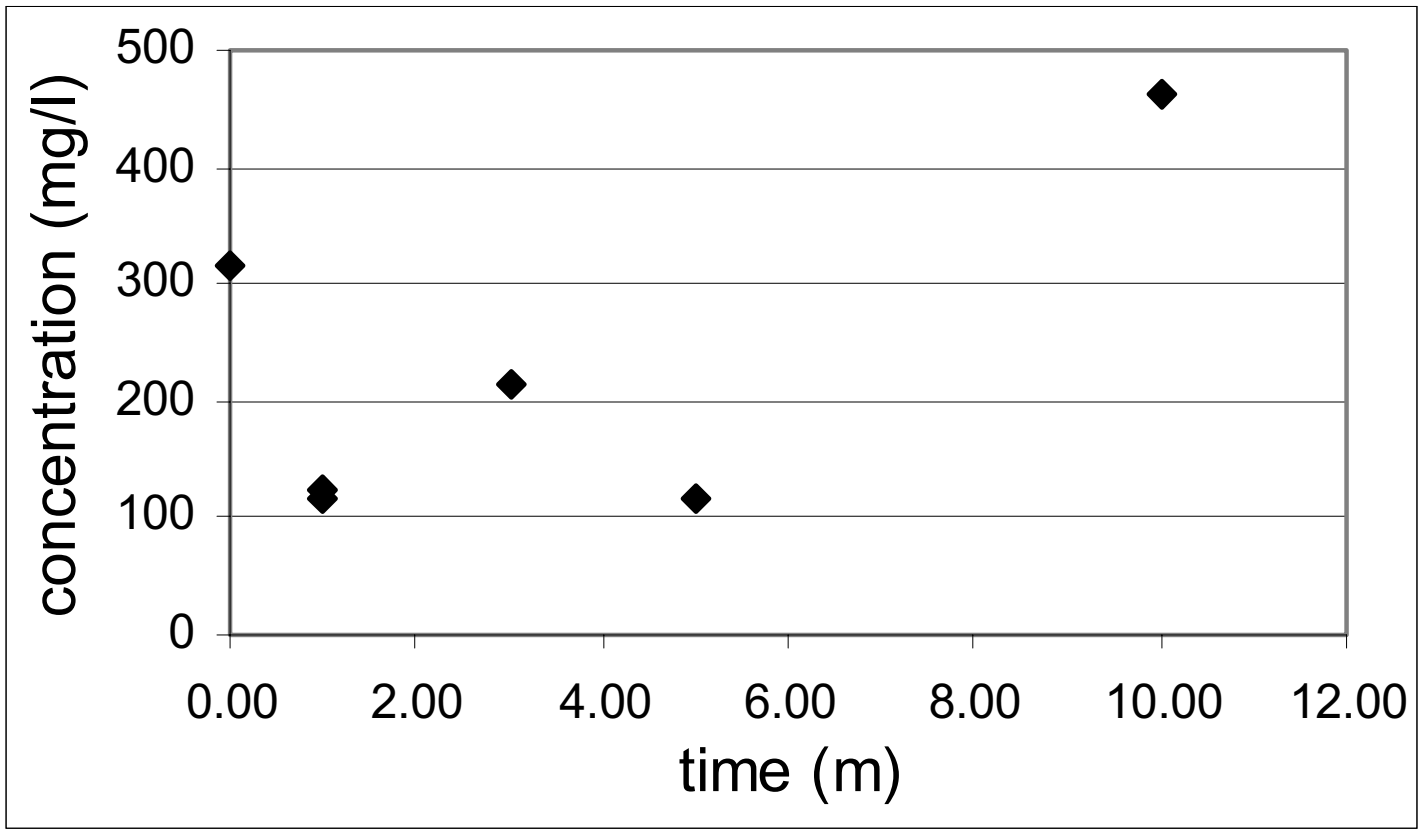


Figure B-8: Experiment 4, CERGRENE (multiple columns) [18 cm, C/L, Microsand]

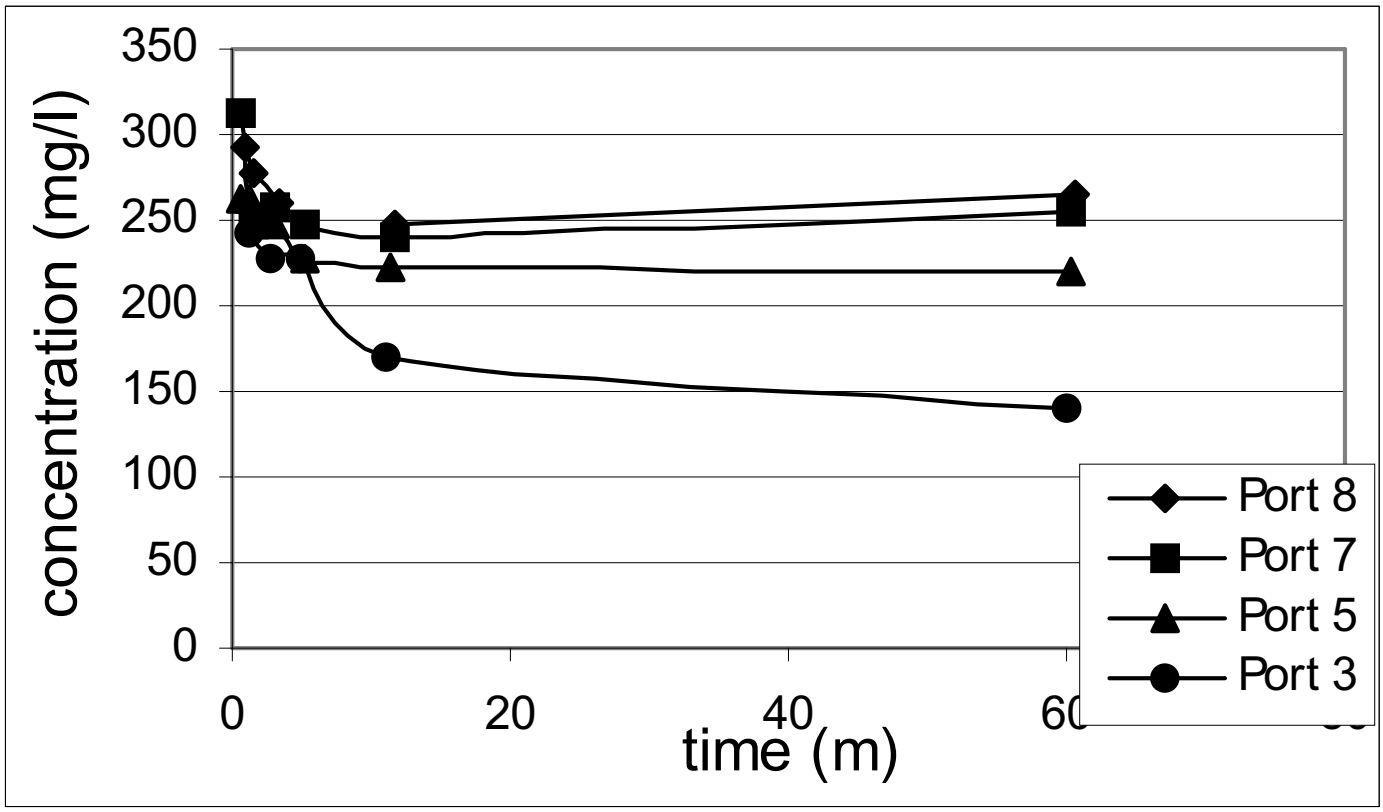


Figure B-9: Experiment 5, Long Column [18 cm, L/C, Neshaminy]

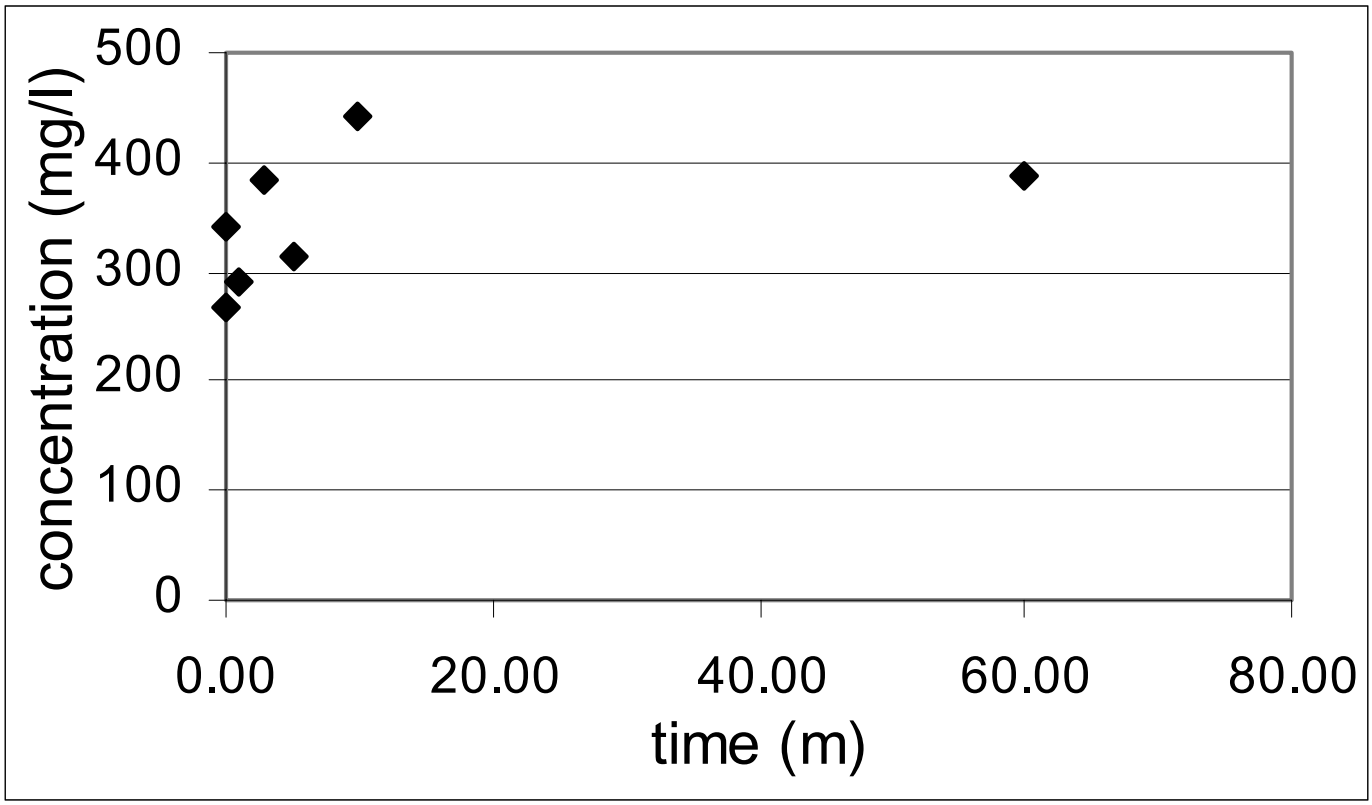


Figure B-10: Experiment 5, CERGRENE (multiple columns) [18 cm, L/C, Neshaminy]

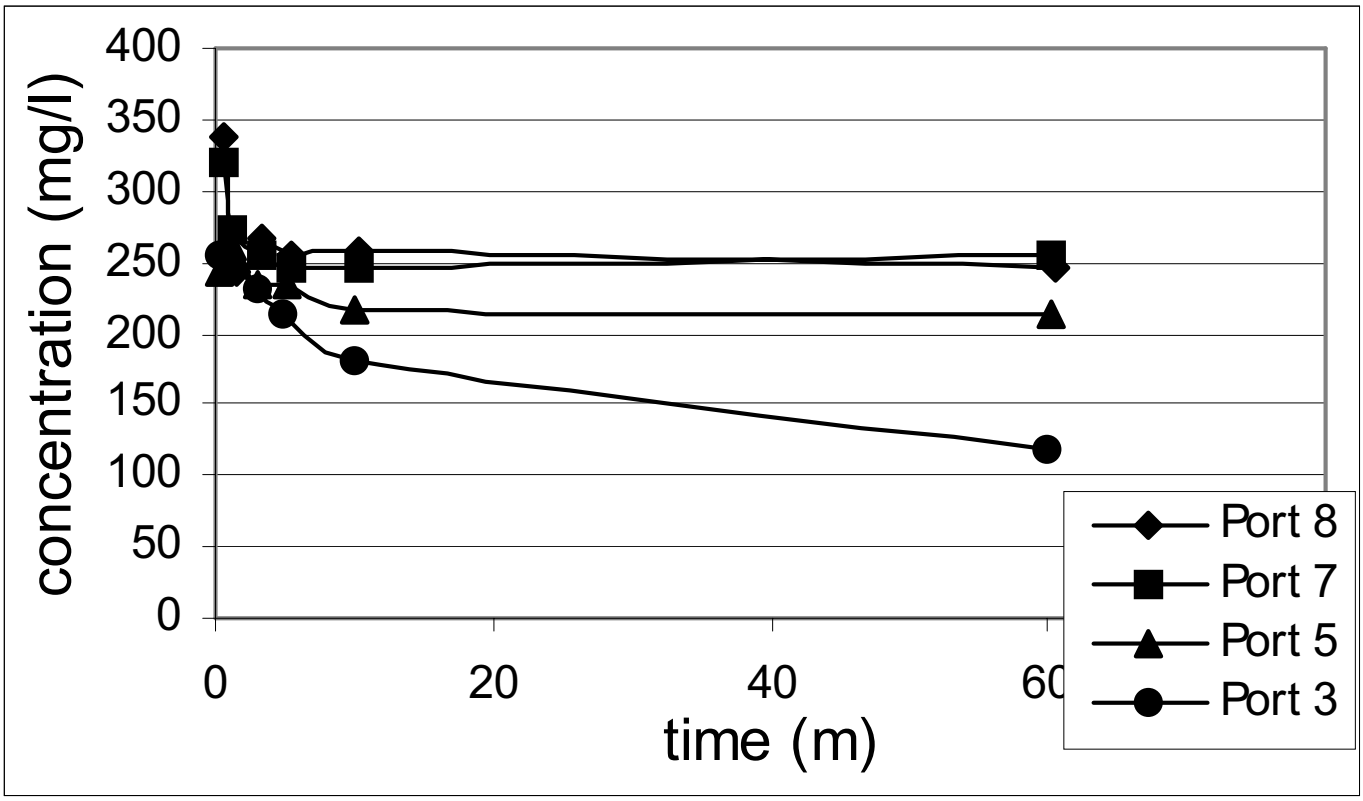


Figure B-11: Experiment 6, Long Column [36 cm, L/C, Neshaminy]

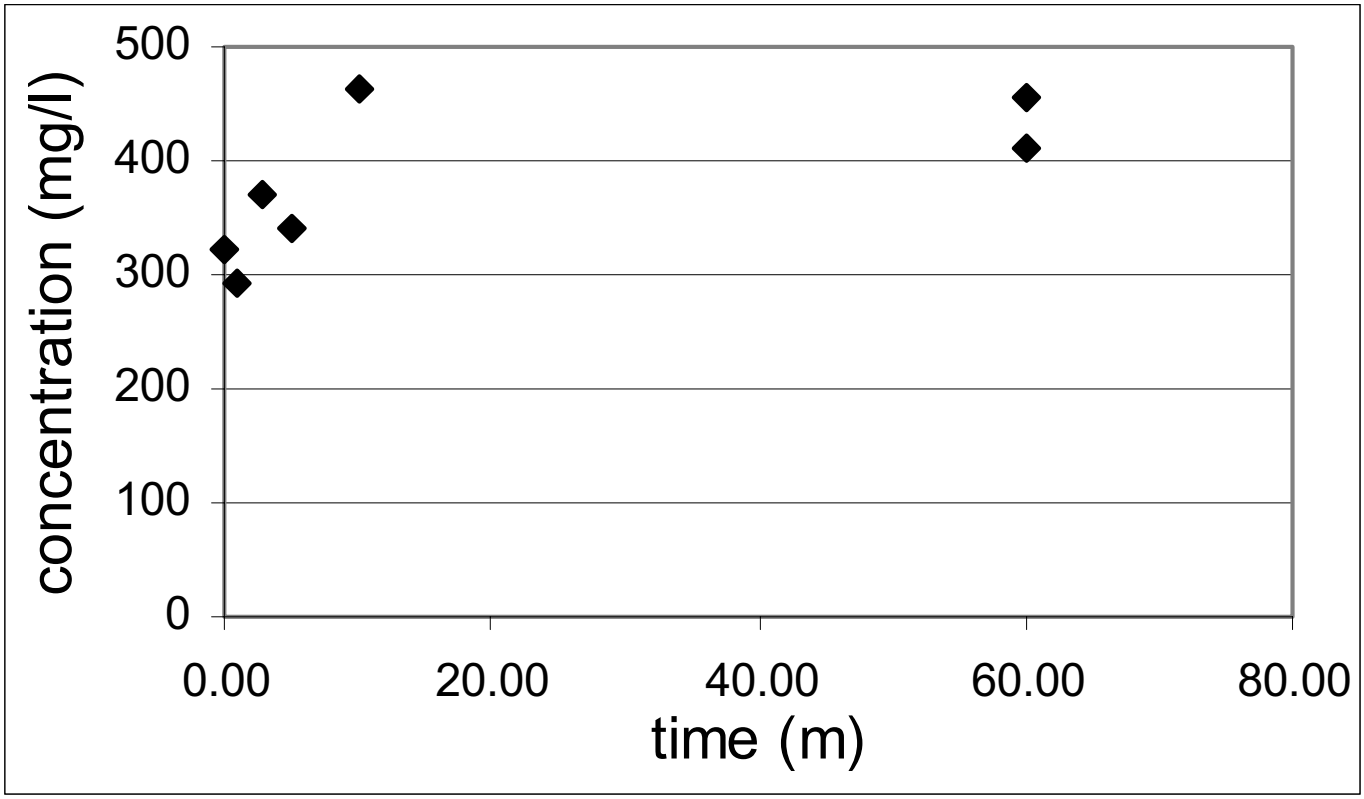


Figure B-12: Experiment 6, CERGRENE (multiple columns) [36 cm, L/C, Neshaminy]

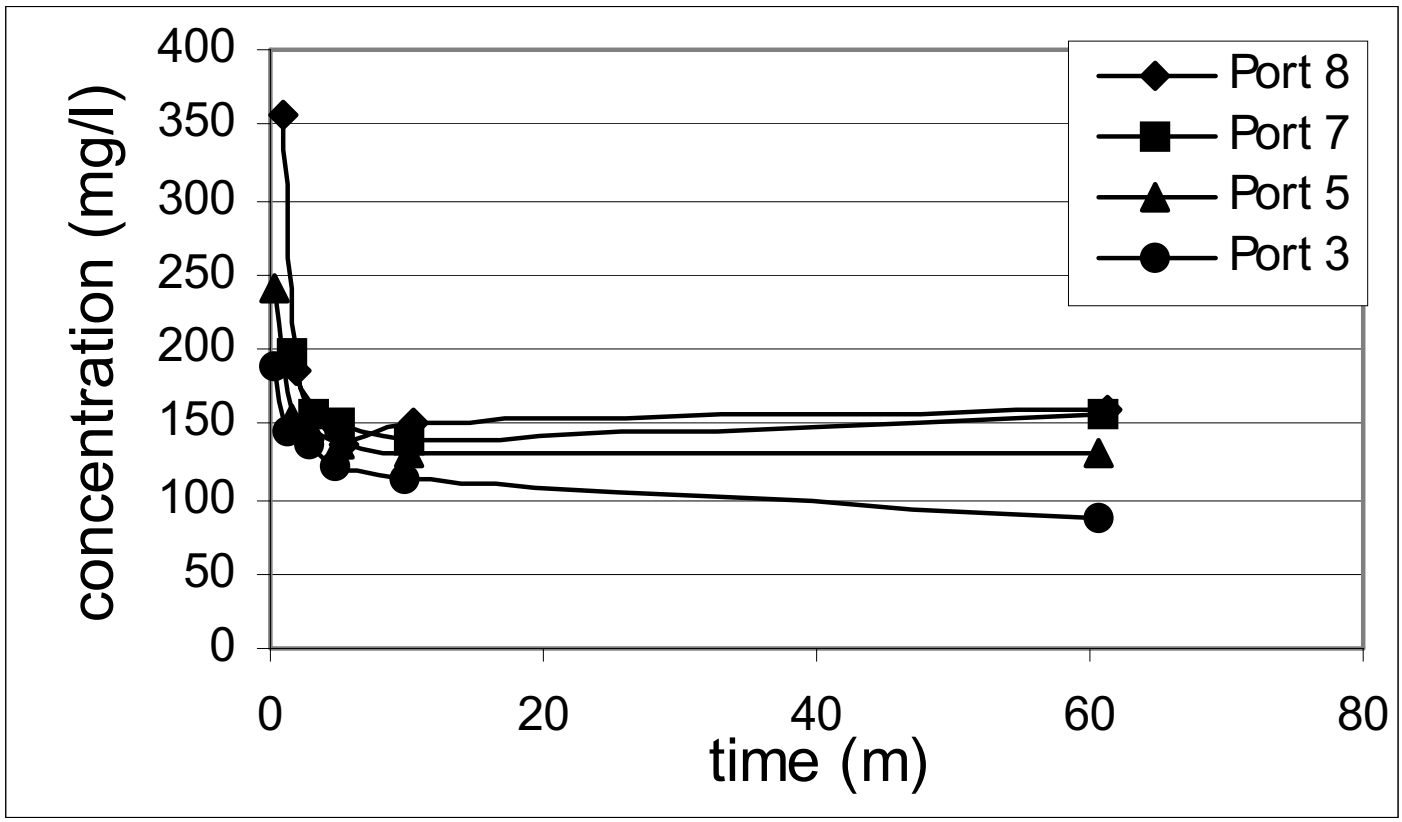


Figure B-13: Experiment 7, Long Column [18 cm, C/L, Mixture]

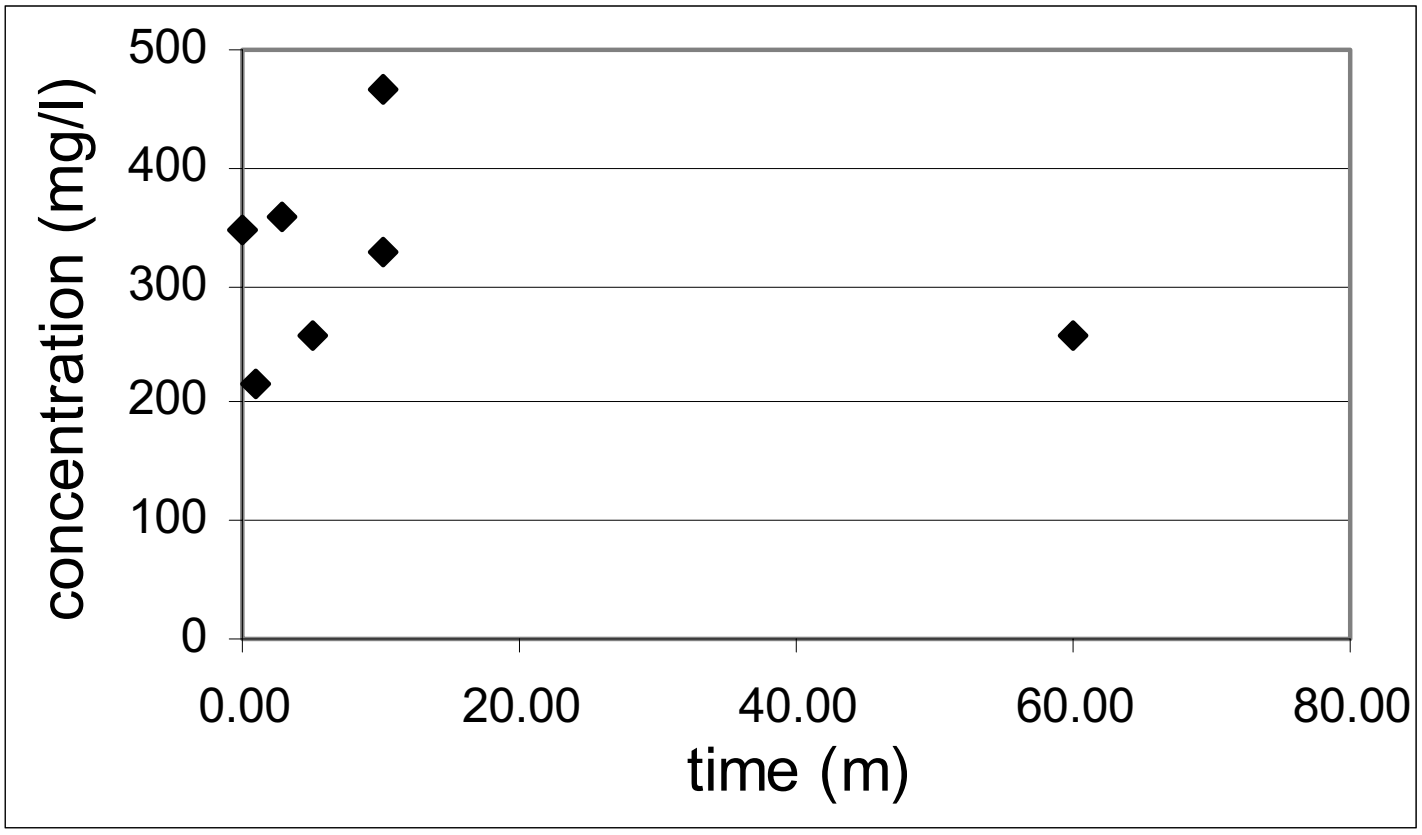


Figure B-14: Experiment 7, CERGRENE (multiple columns) [18 cm, C/L, Mixture]

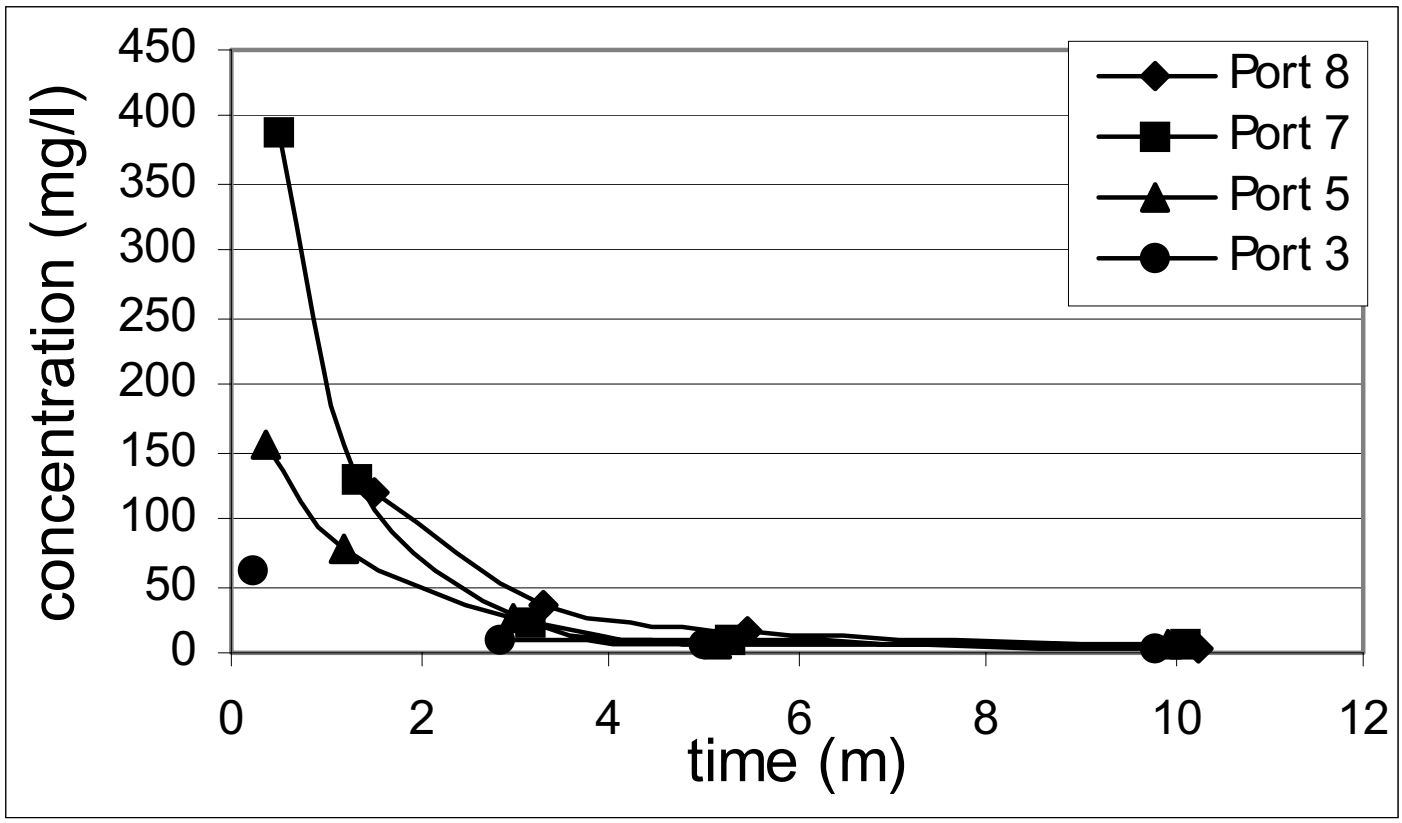


Figure B-15: Experiment 8, Long Column [18 cm, L/C, Microsand]

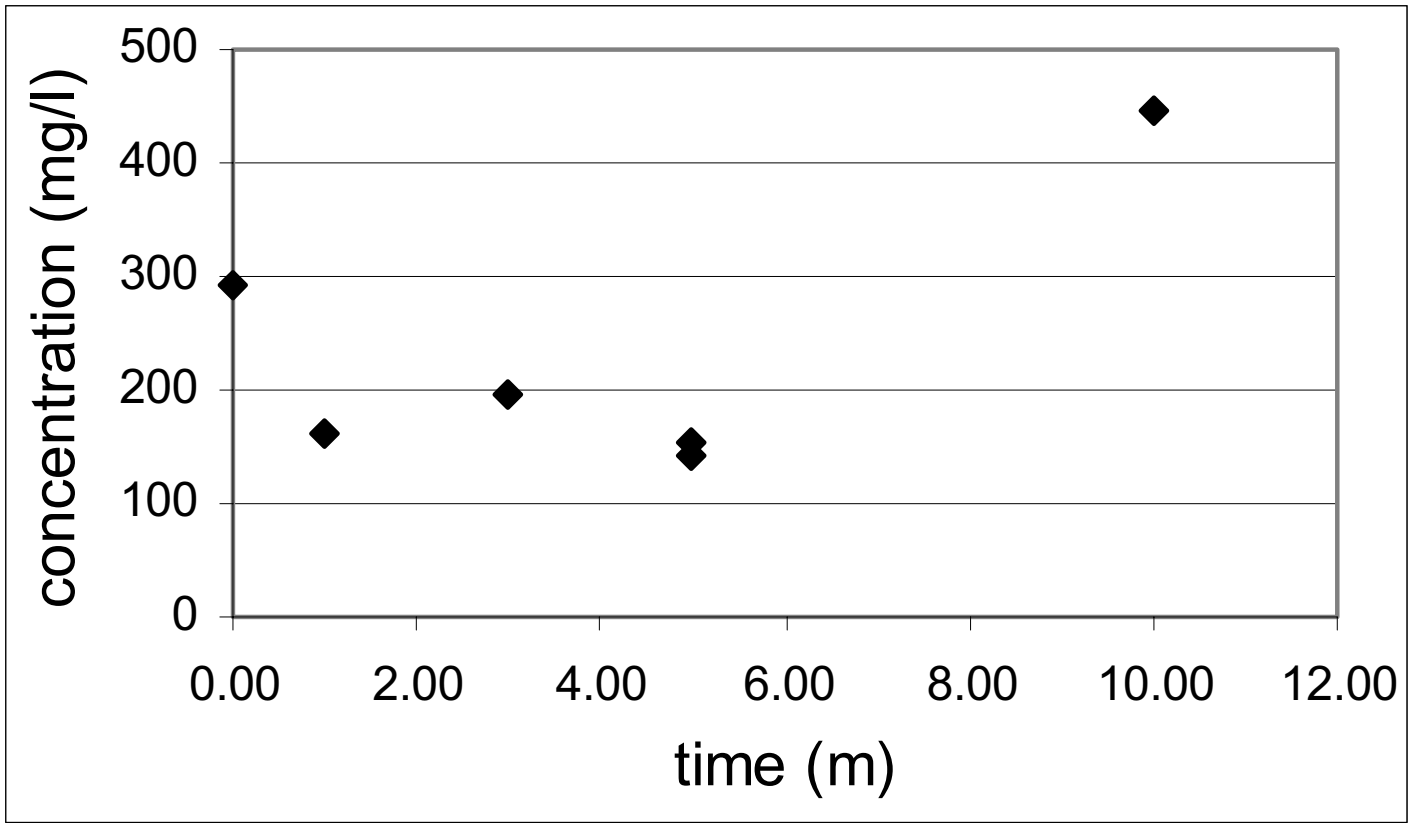


Figure B-16: Experiment 8, CERGRENE (multiple columns) [18 cm, L/C, Microsand]

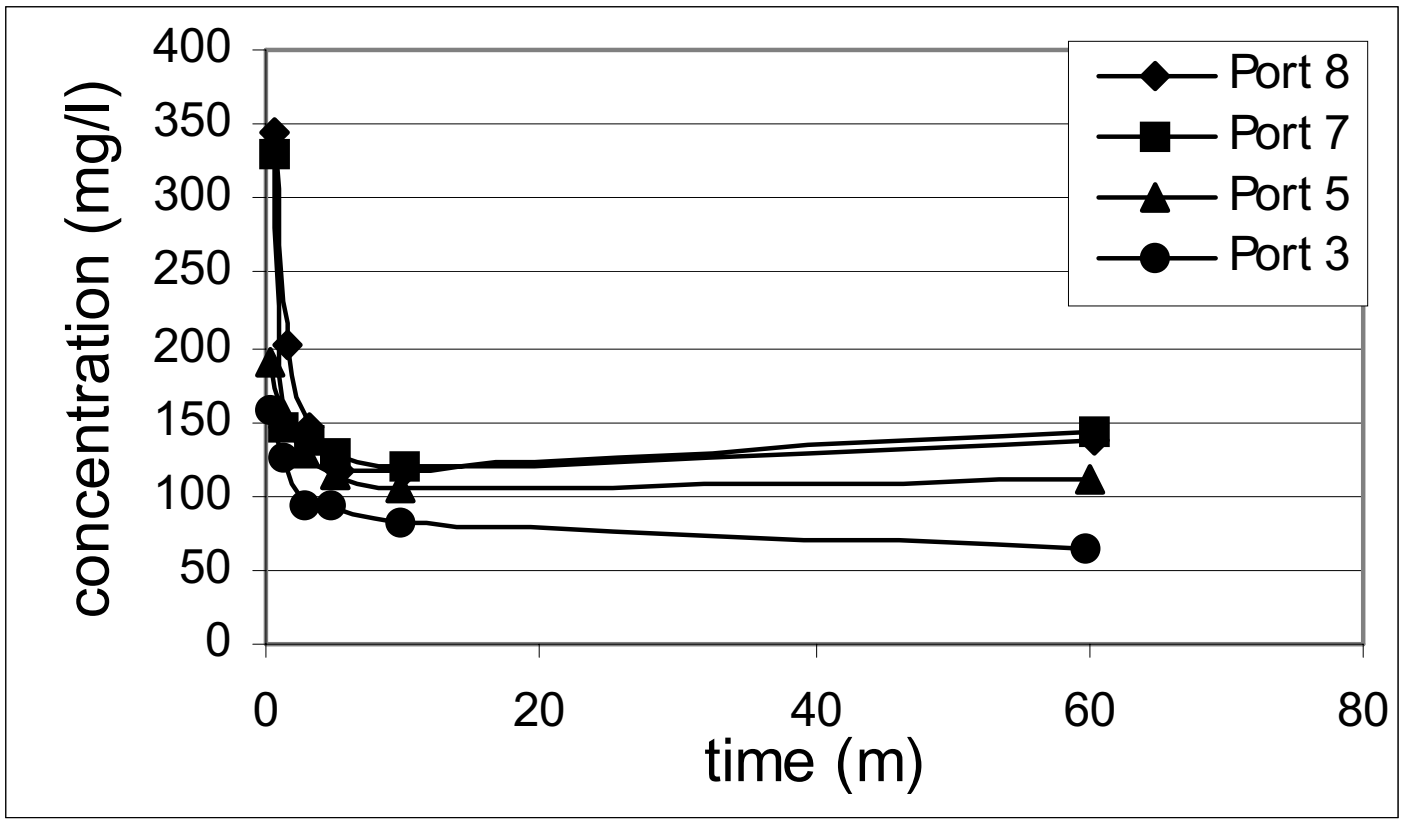


Figure B-17: Experiment 9, Long Column [18 cm, L/C, Mixture]

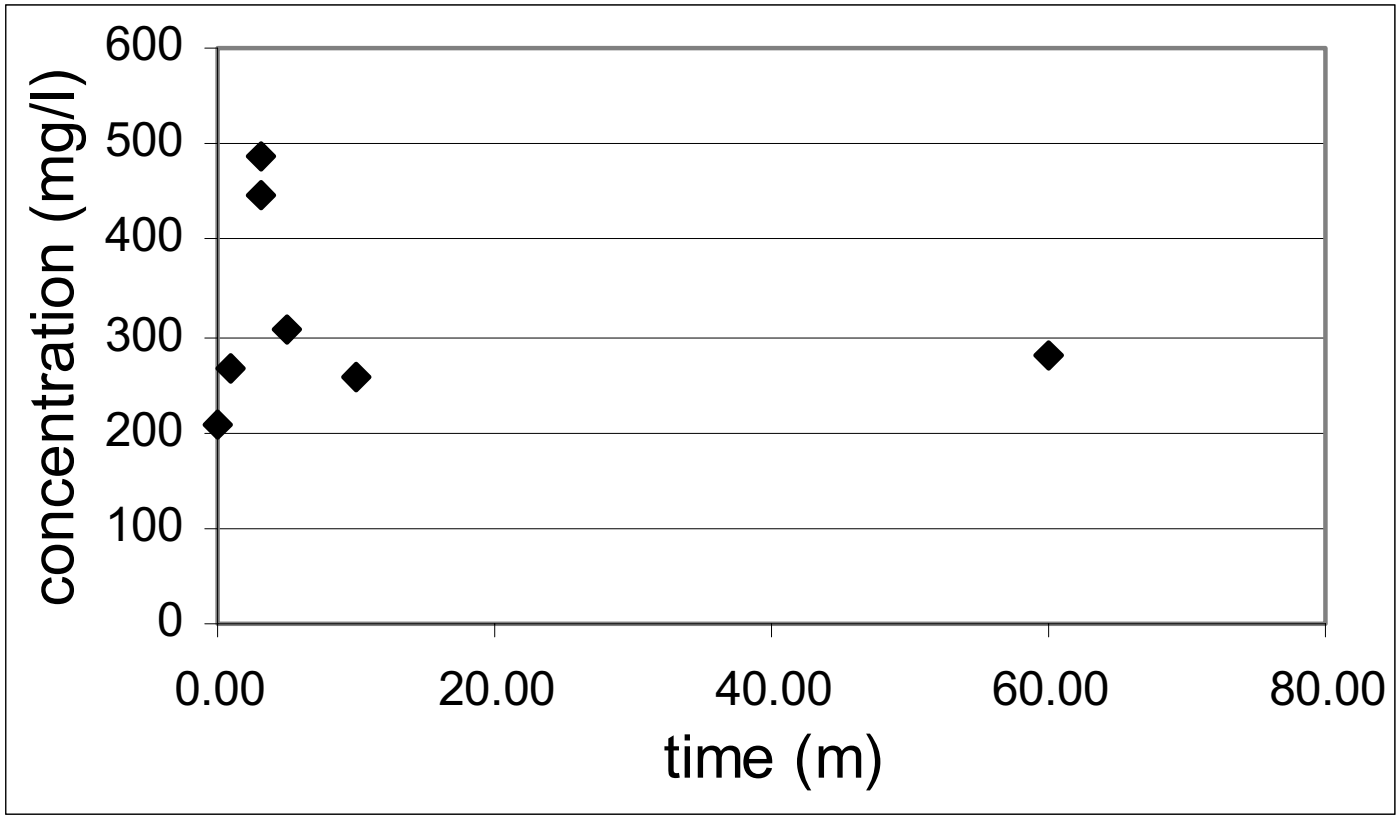


Figure B-18: Experiment 9, CERGRENE (multiple columns, randomized) [18 cm, L/C, Mixture]

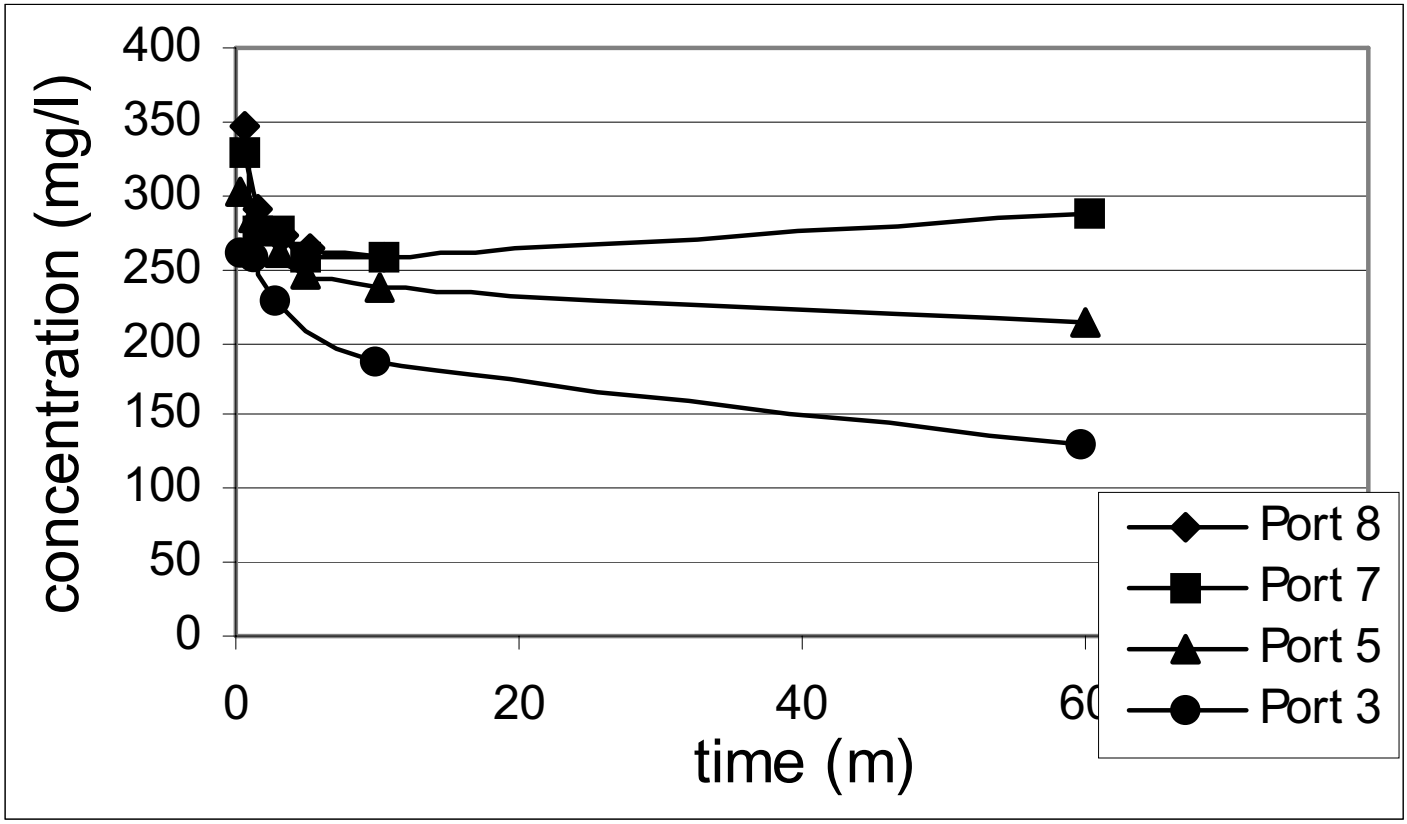


Figure B-19: Experiment 10, Long Column [36 cm, L/C, Neshaminy]

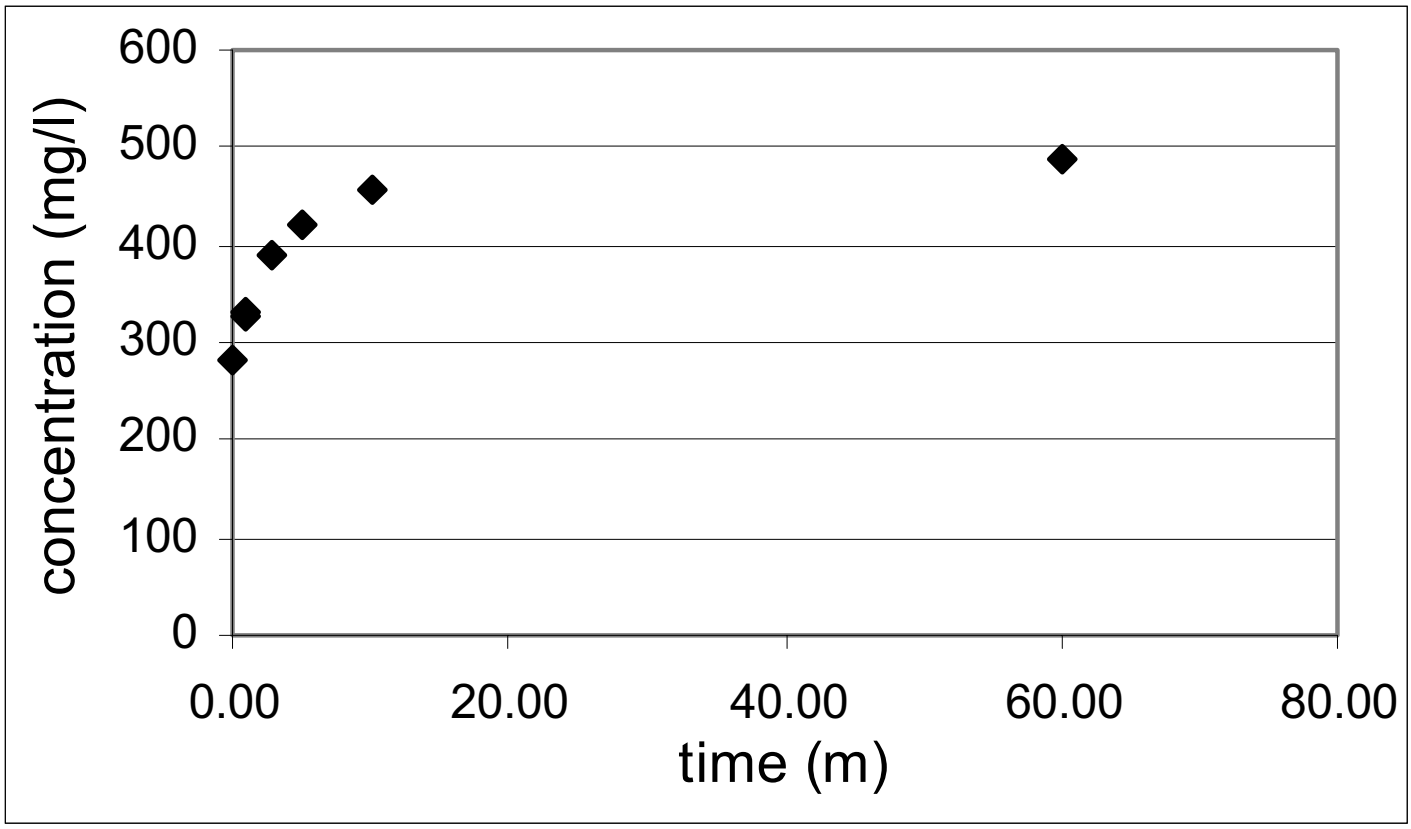


Figure B-20: Experiment 10, CERGRENE (one column) [36 cm, L/C, Neshaminy]

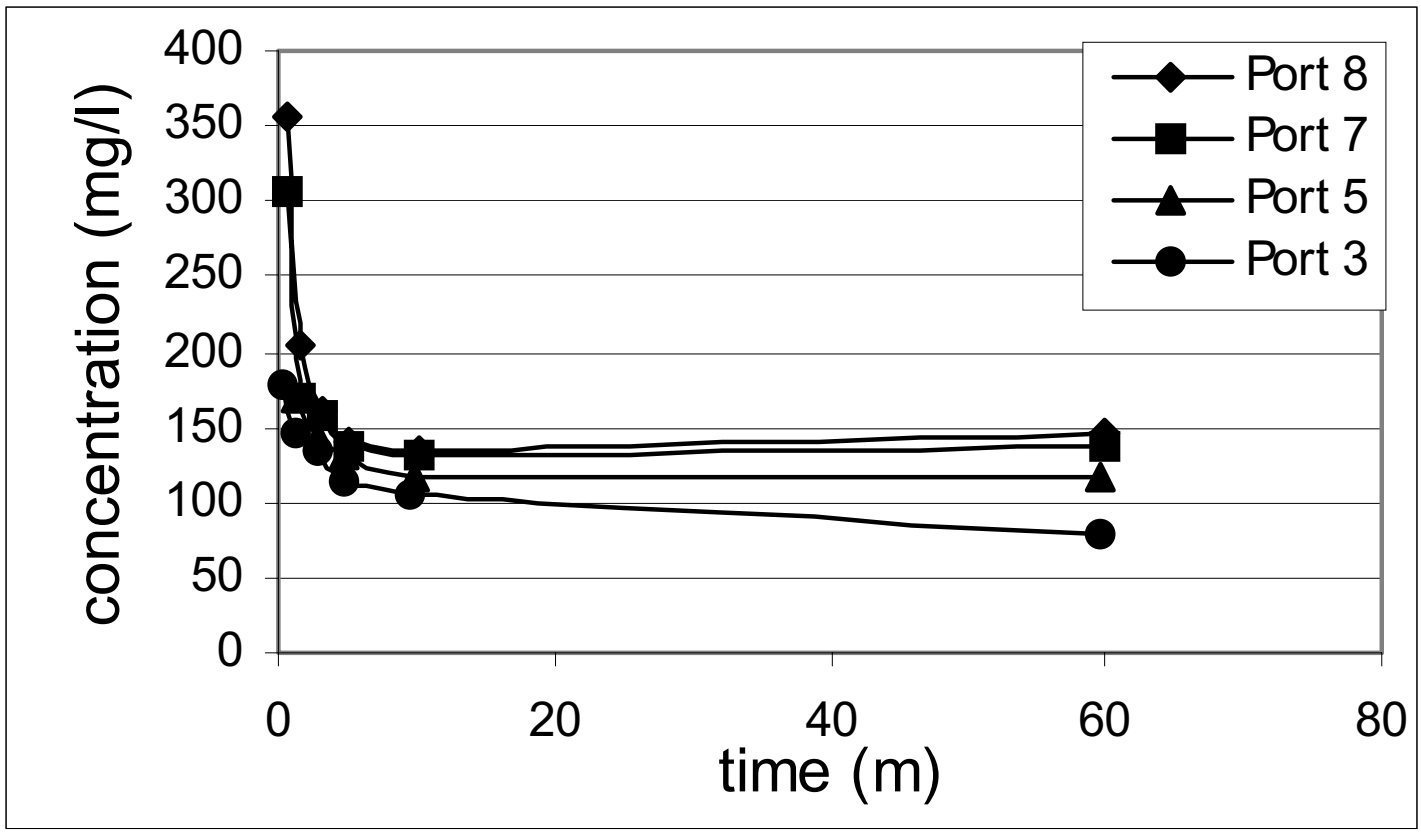


Figure B-21: Experiment 11, Long Column [36 cm, L/C, Mixture]

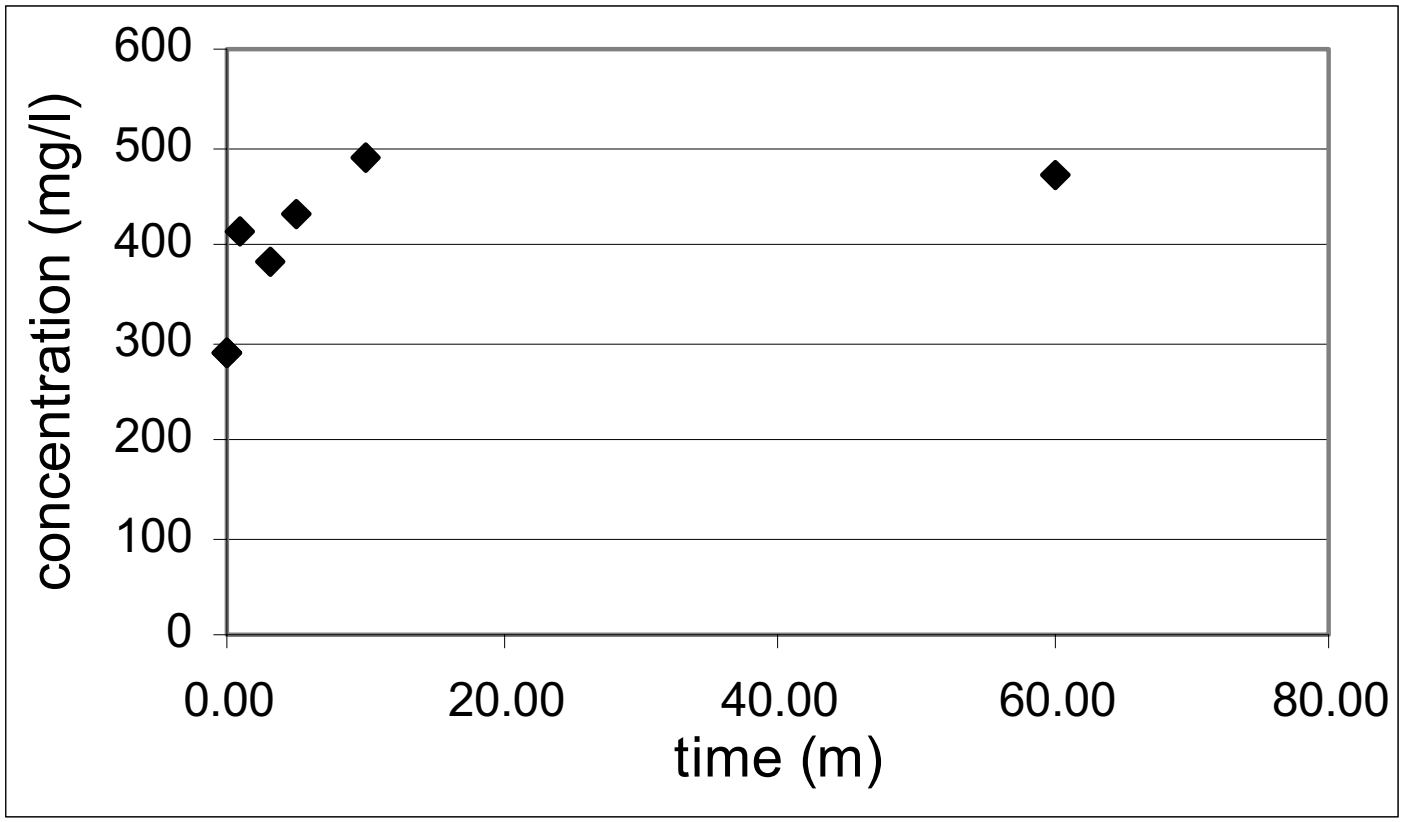


Figure B-22: Experiment 11, CERGRENE (one column) [36 cm, L/C, Mixture]

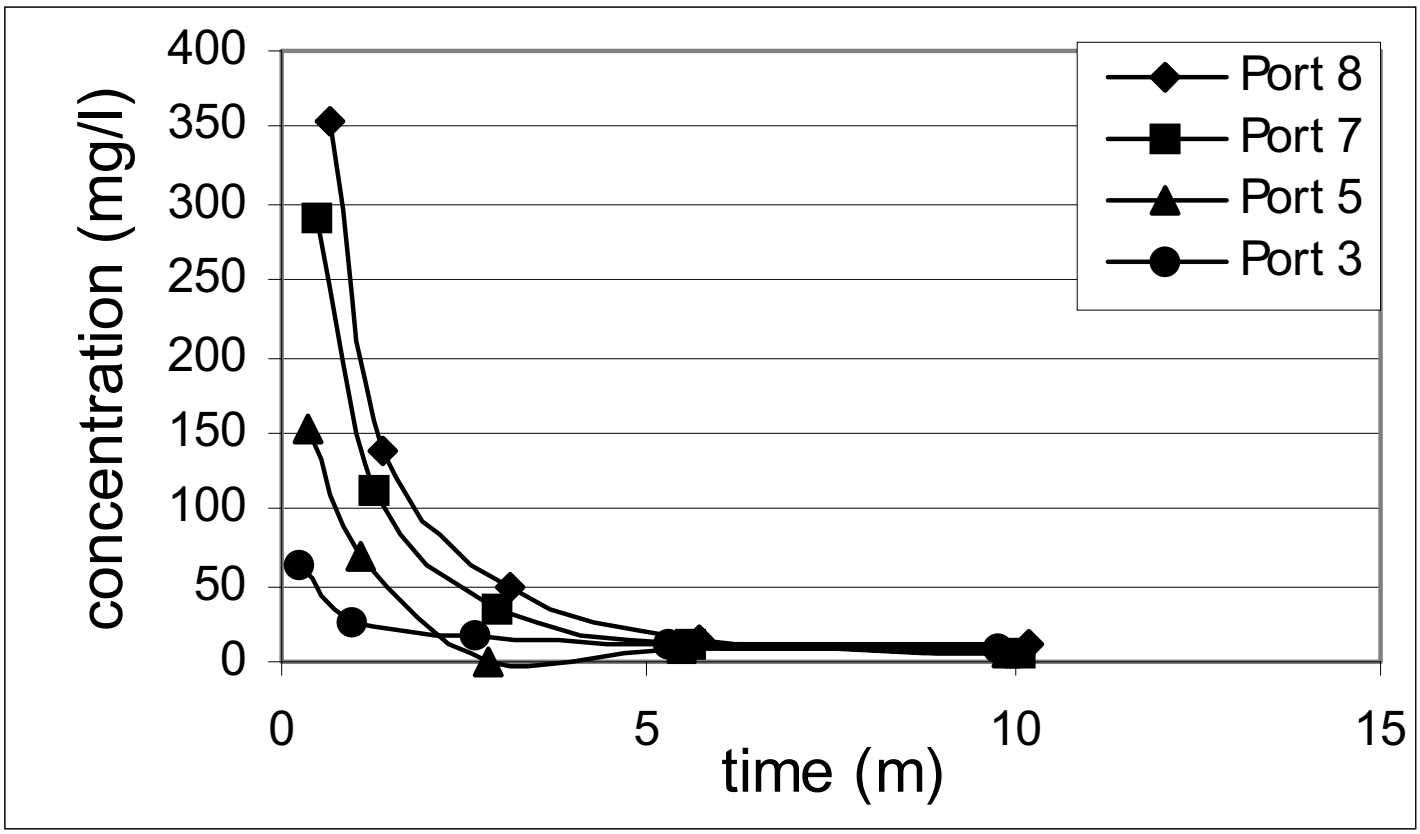


Figure B-23: Experiment 12, Long Column [18 cm, L/C, Microsand]

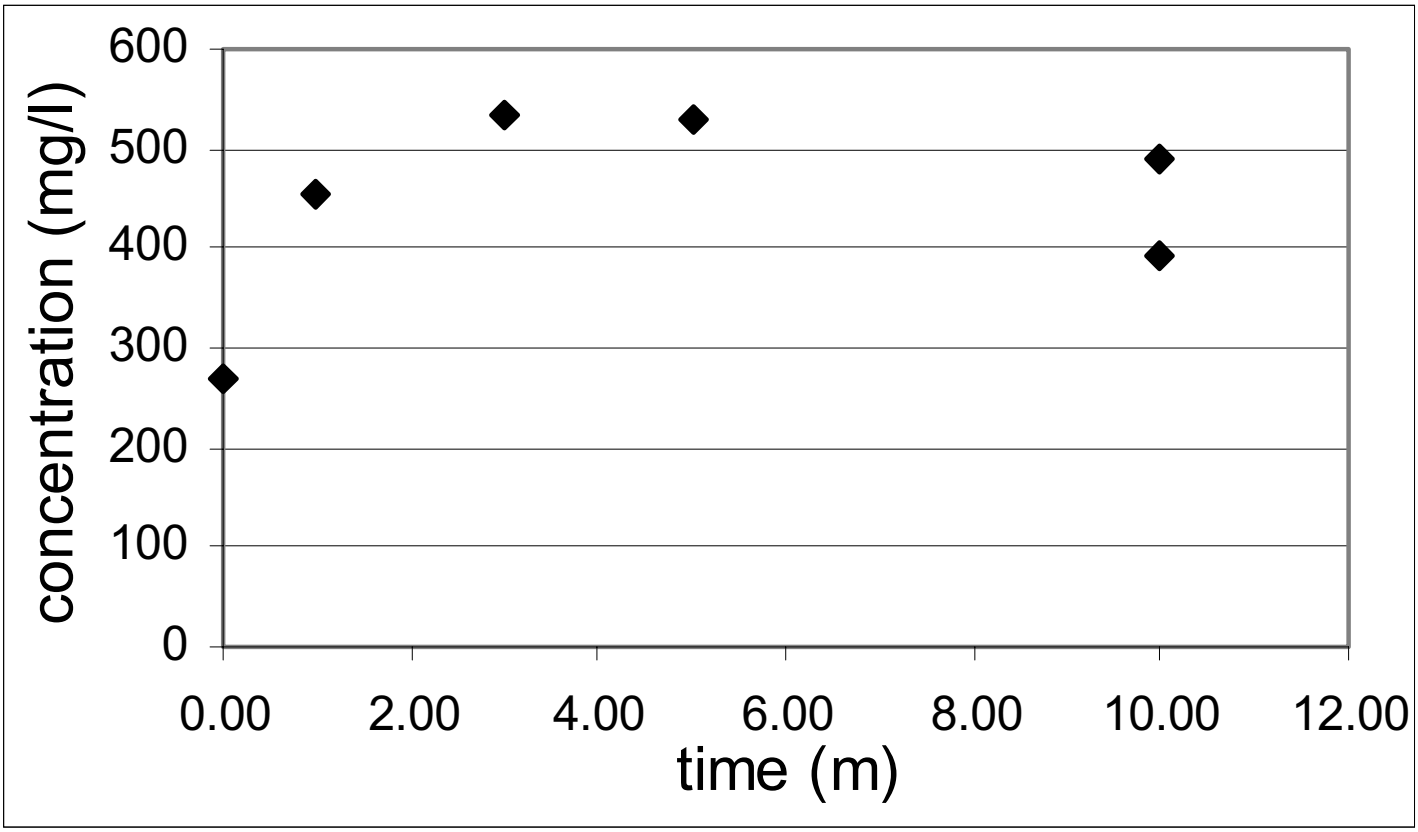


Figure B-24: Experiment 12, CERGRENE (one column) [18 cm, L/C, Microsand]

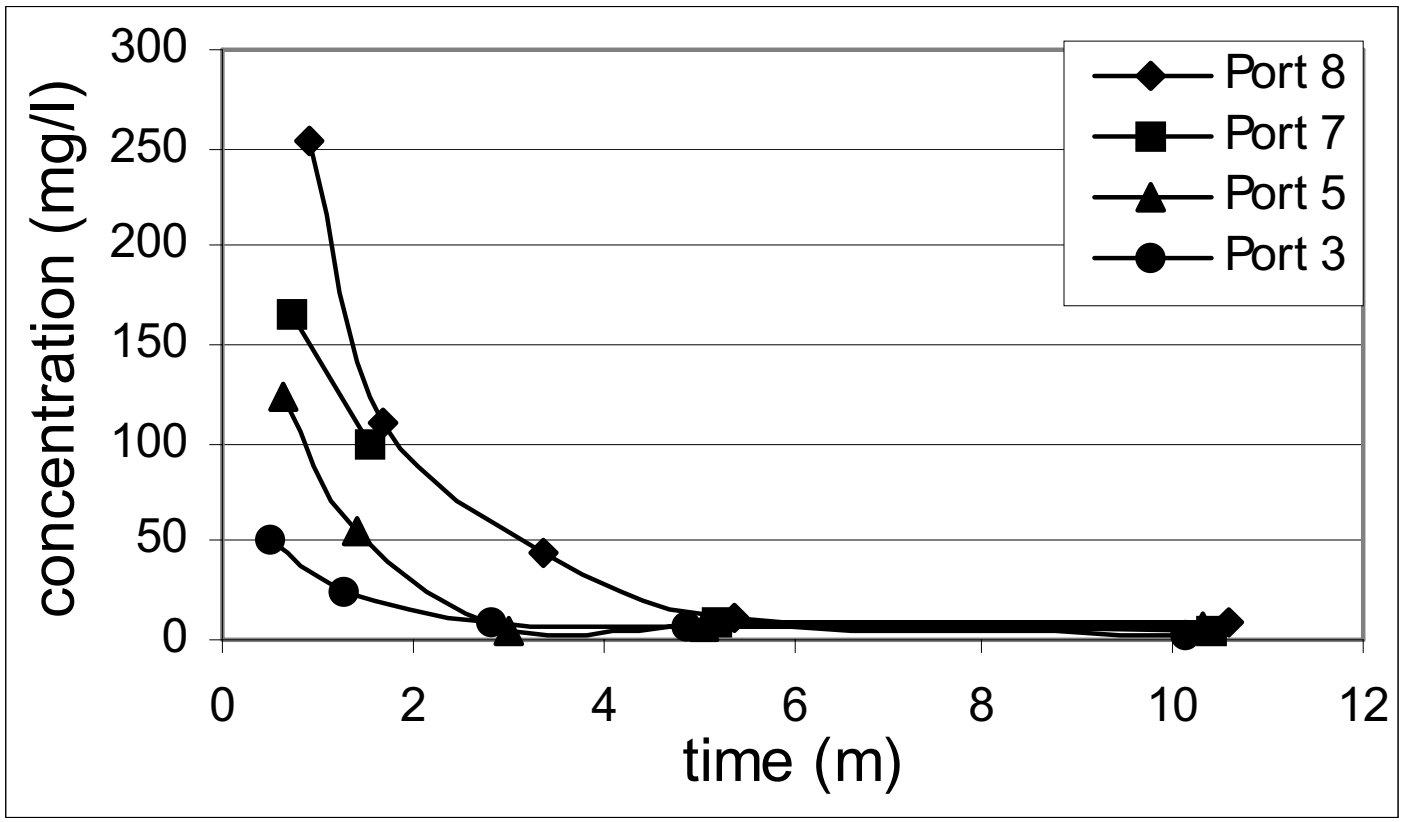


Figure B-25: Experiment 13, Long Column [36 cm, C/L, Microsand]

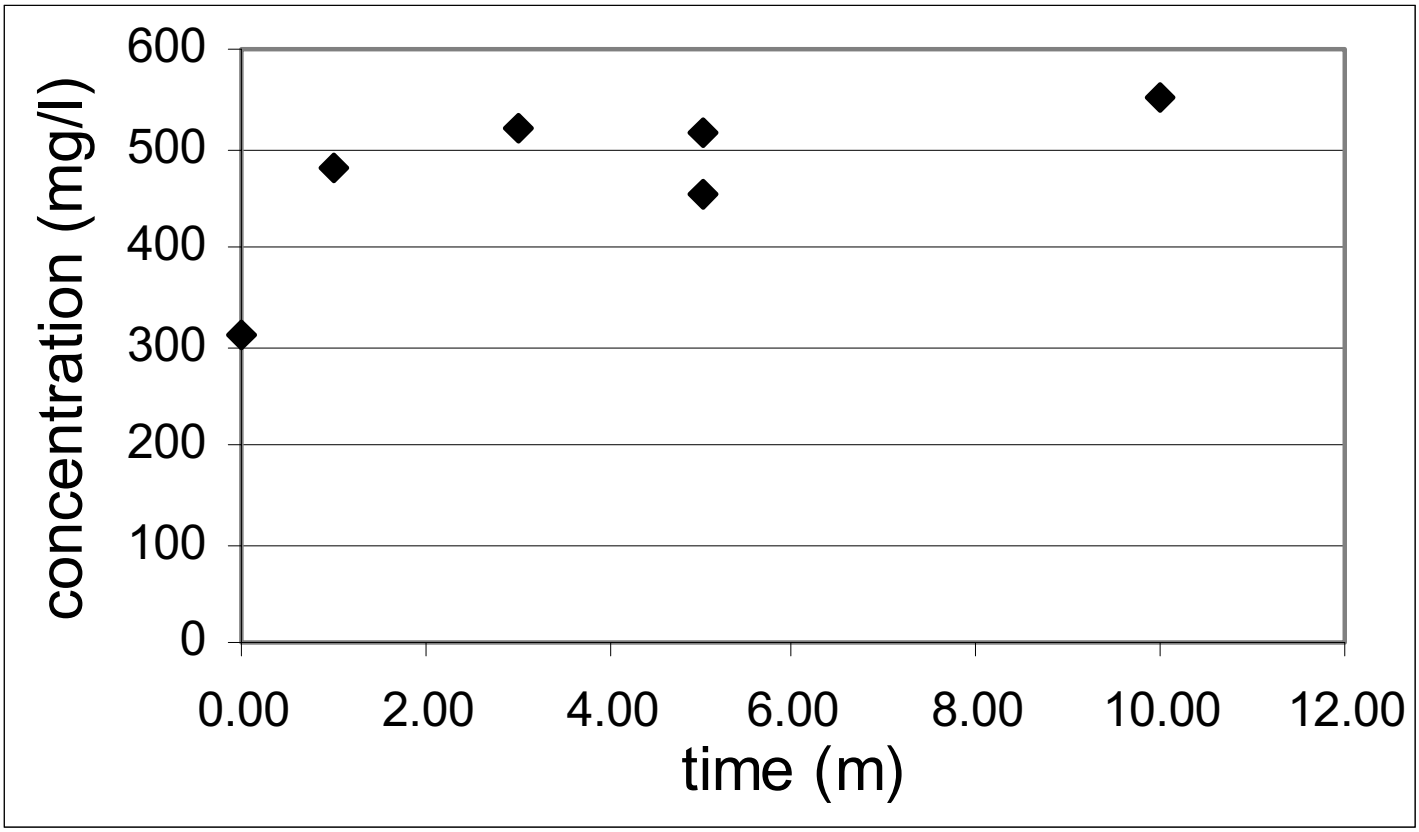


Figure B-26: Experiment 13, CERGRENE (one column) [36 cm, C/L, Microsand]

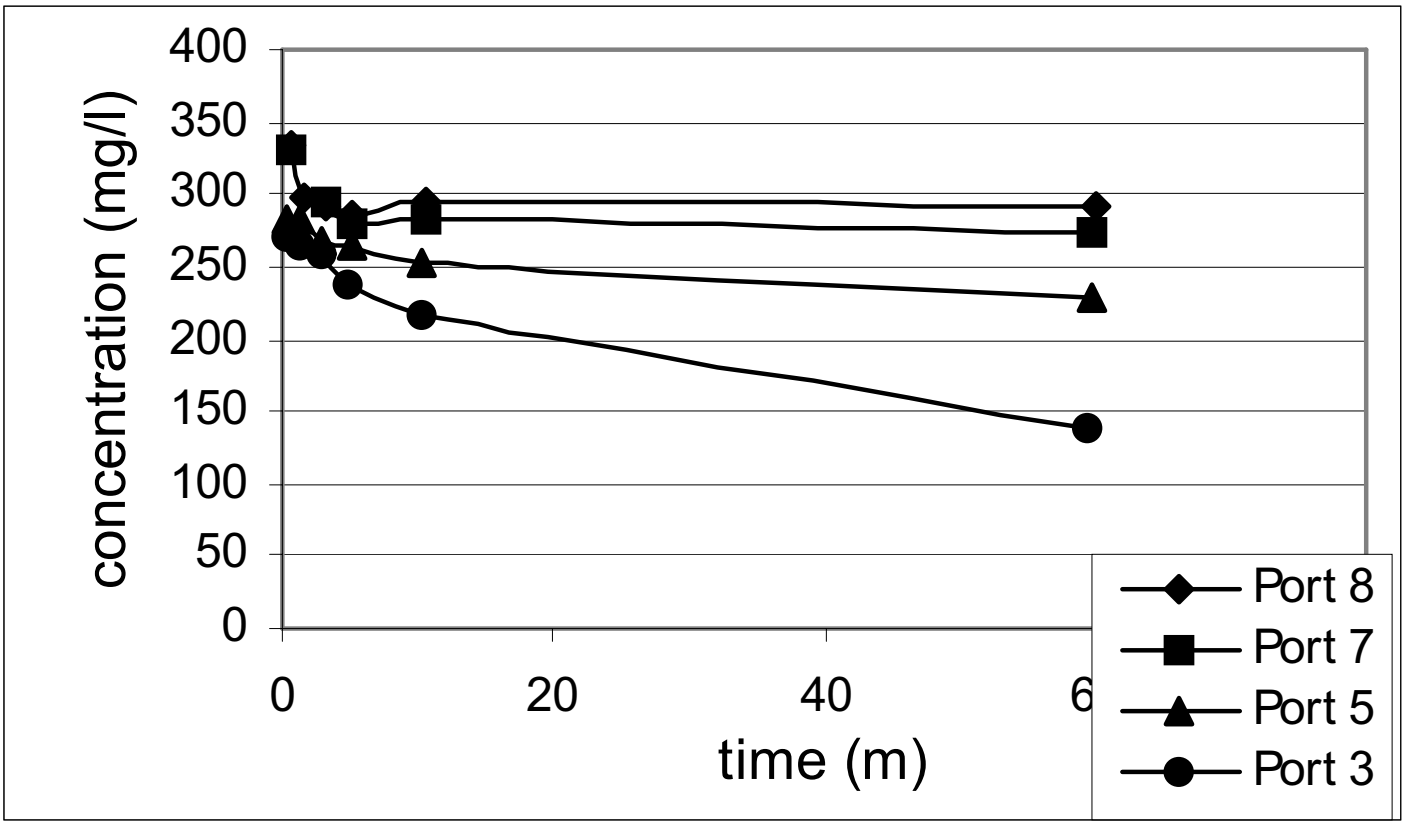


Figure B-27: Experiment 14, Long Column [18 cm, C/L, Neshaminy]

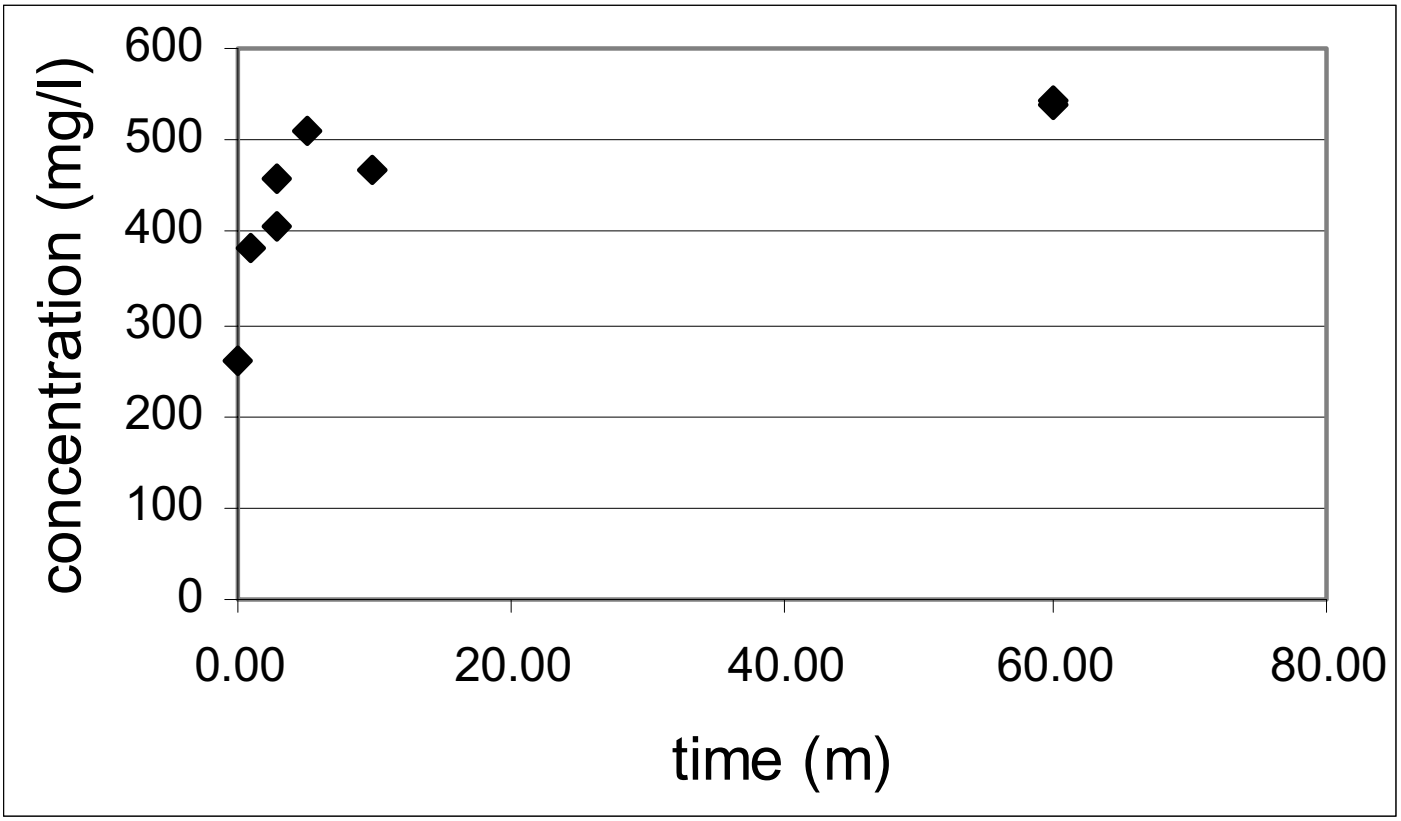


Figure B-28: Experiment 14, CERGRENE (one column) [18 cm, C/L, Neshaminy]

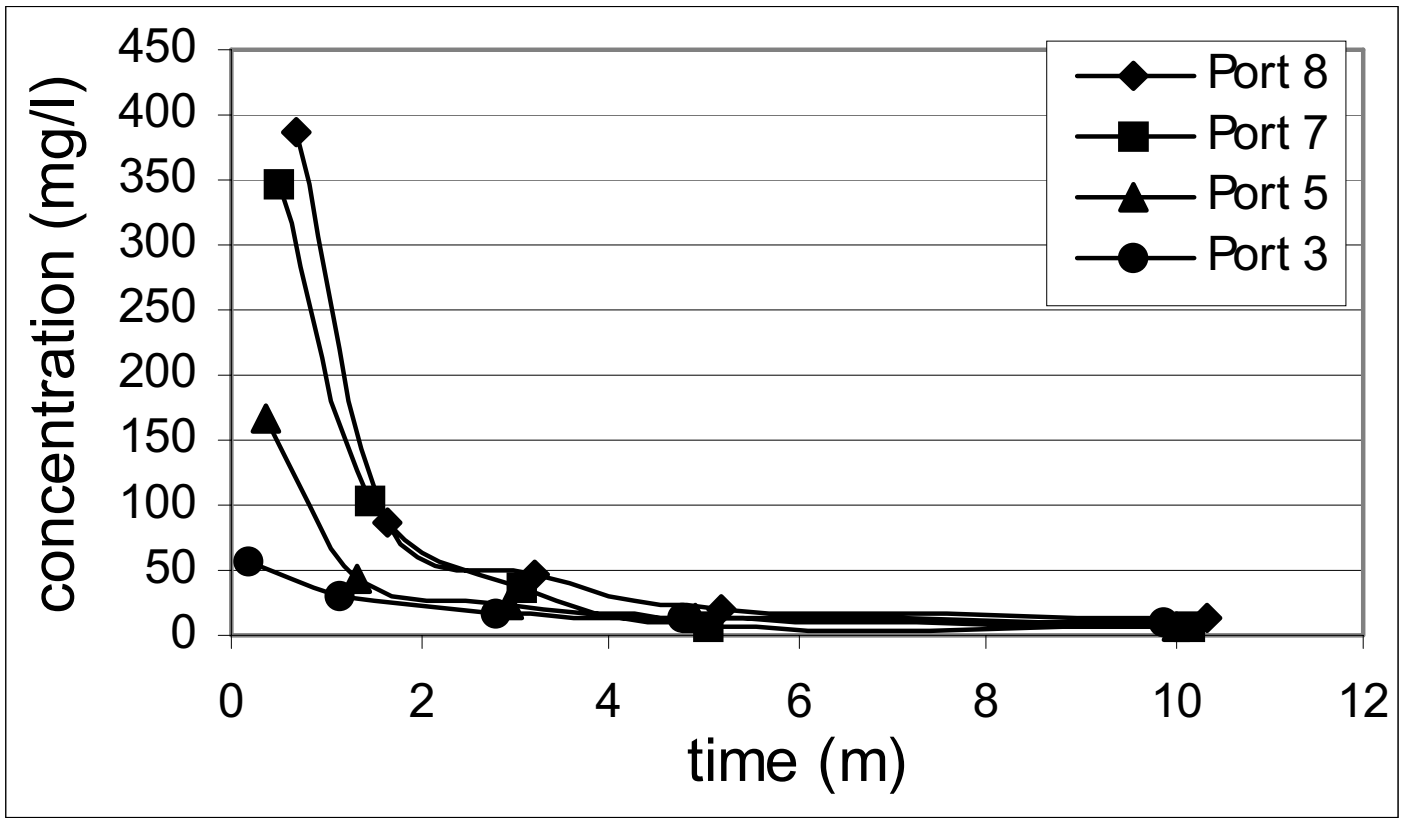


Figure B-29: Experiment 15, Long Column [36 cm, L/C, Microsand]

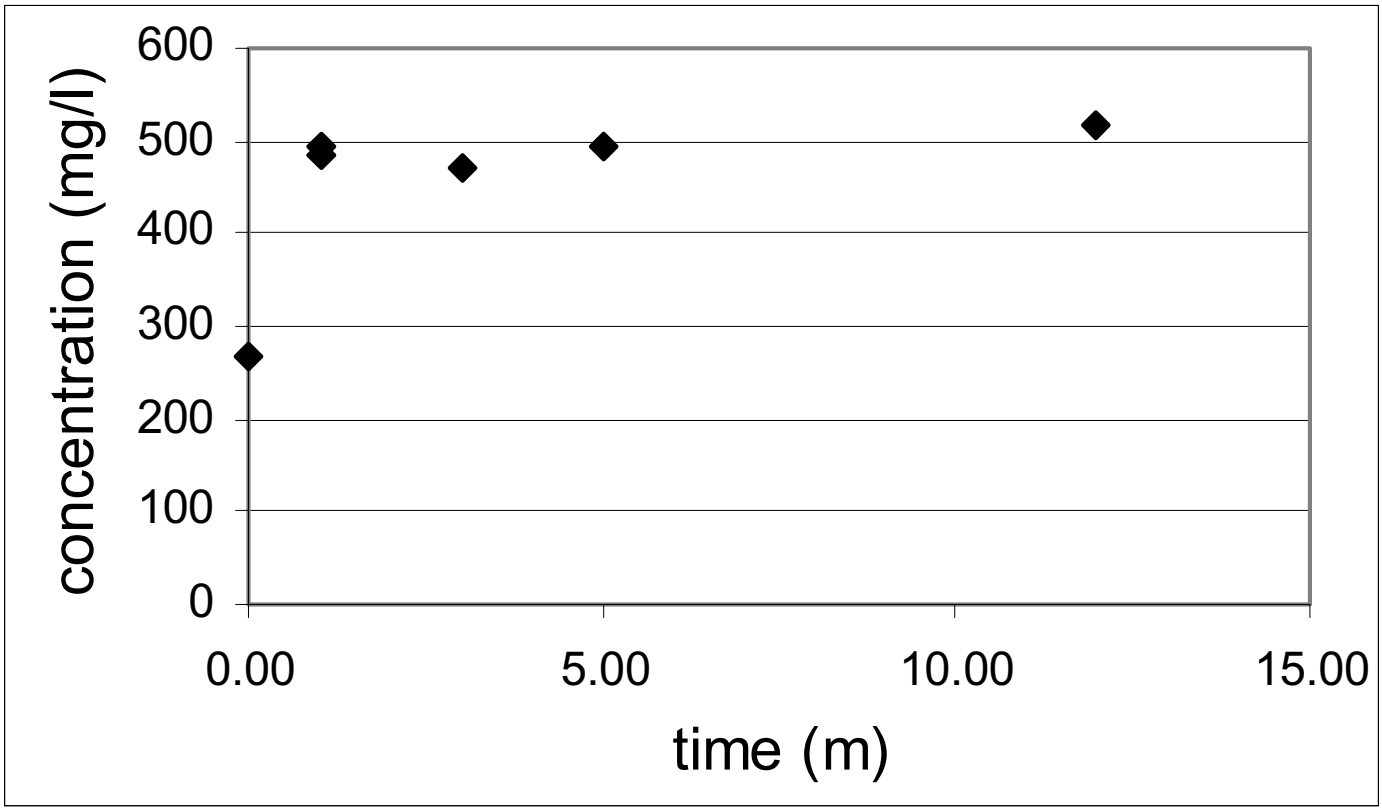


Figure B-30: Experiment 15, CERGRENE (one column) [36 cm, L/C, Microsand]

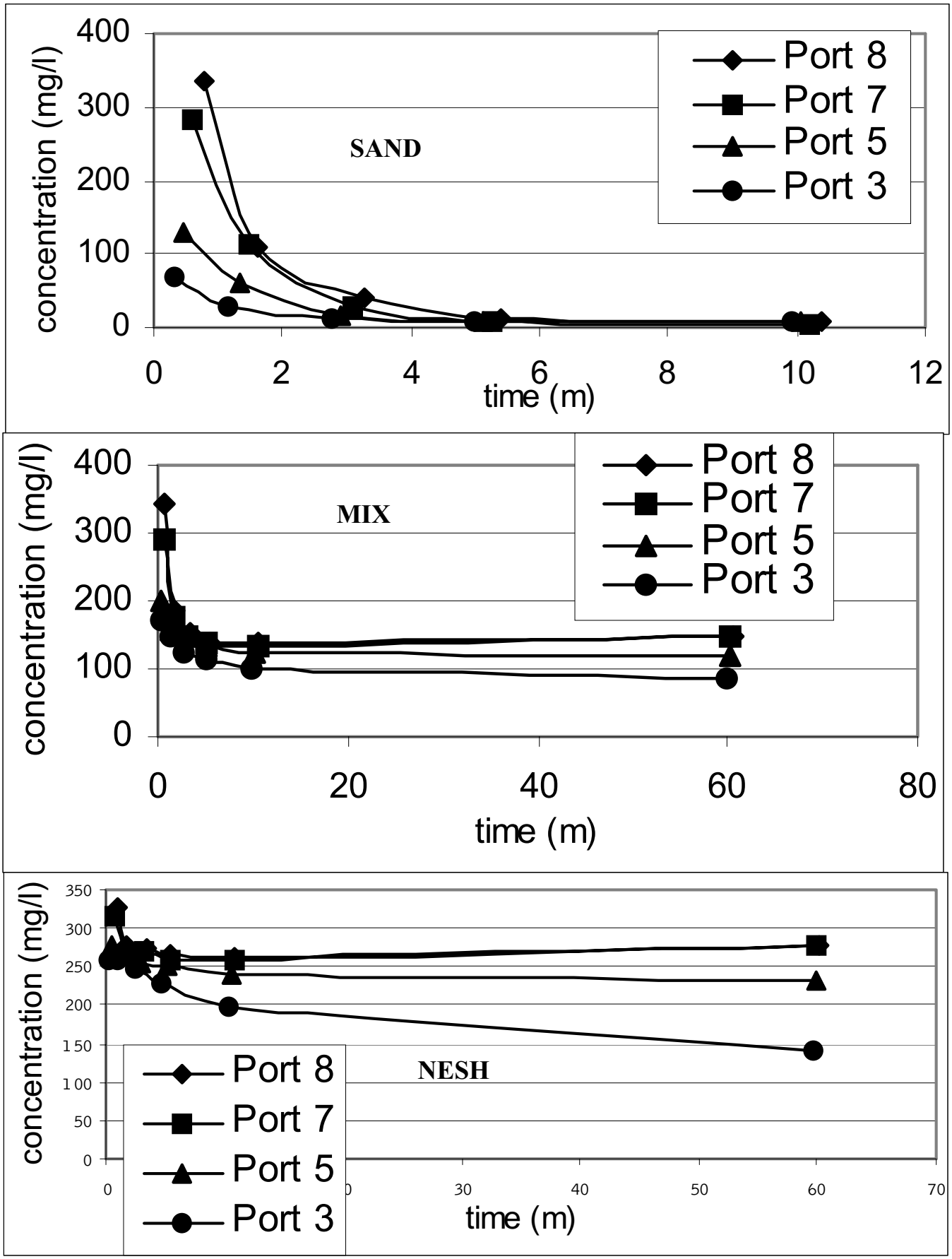


Figure B-31: Average of Long Column Concentrations by Soil Type

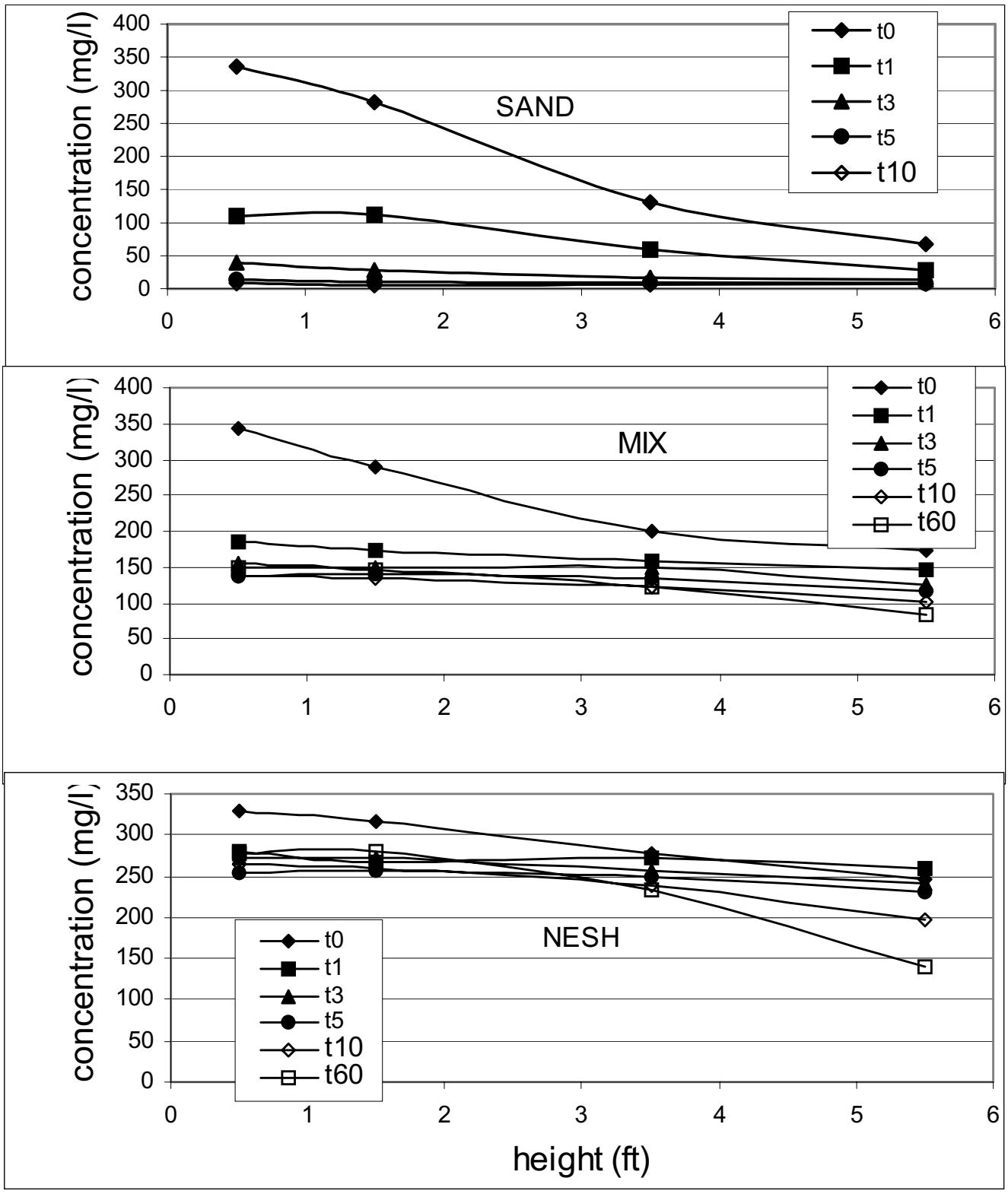


Figure B-32: Average Concentrations for Sand, Mix, and Neshaminy at Each Port and Time Interval

Appendix C

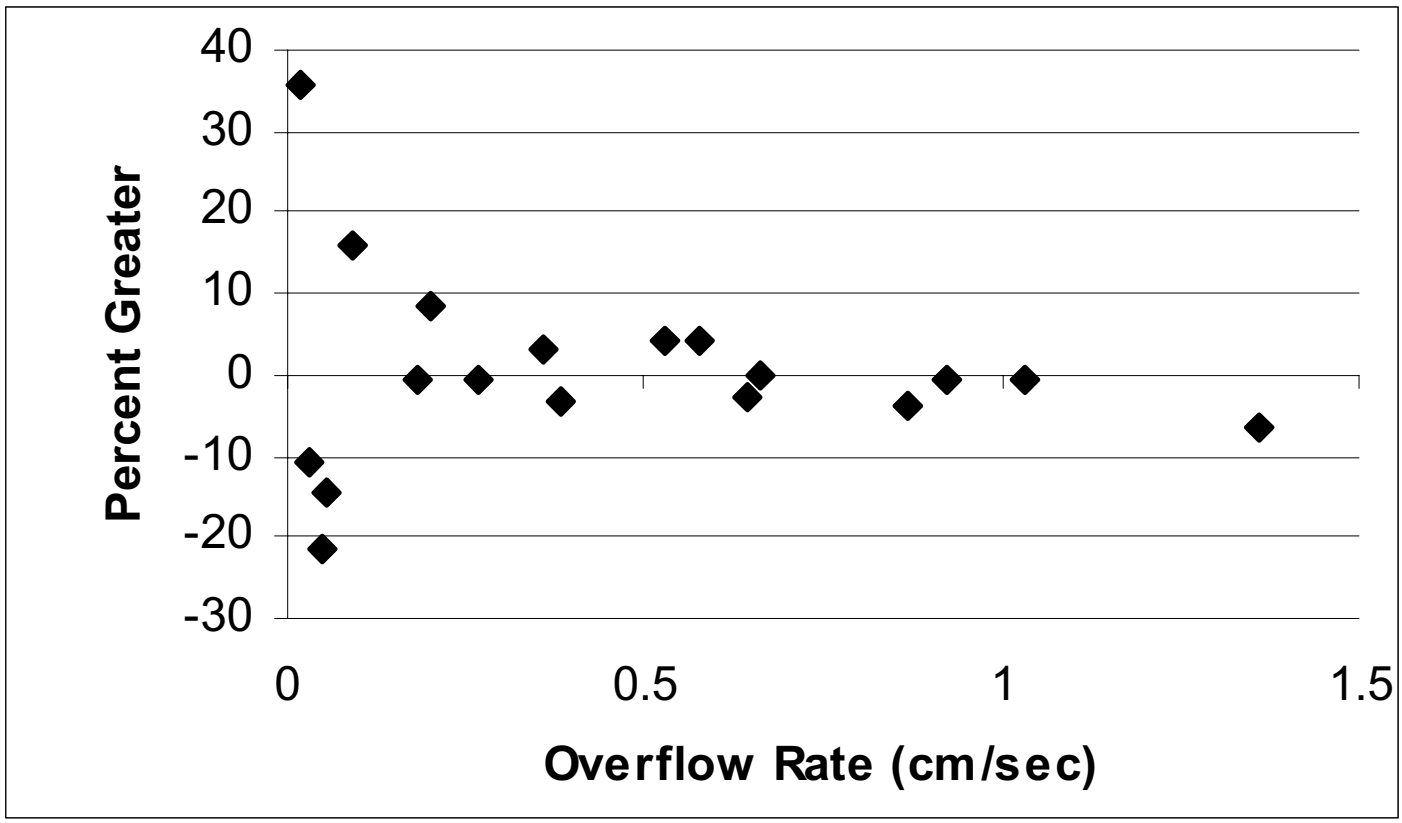


Figure C-1: Percent Removal versus Overflow Rate, Experiment 1, Long Column [36 cm, C/L, Neshaminy]

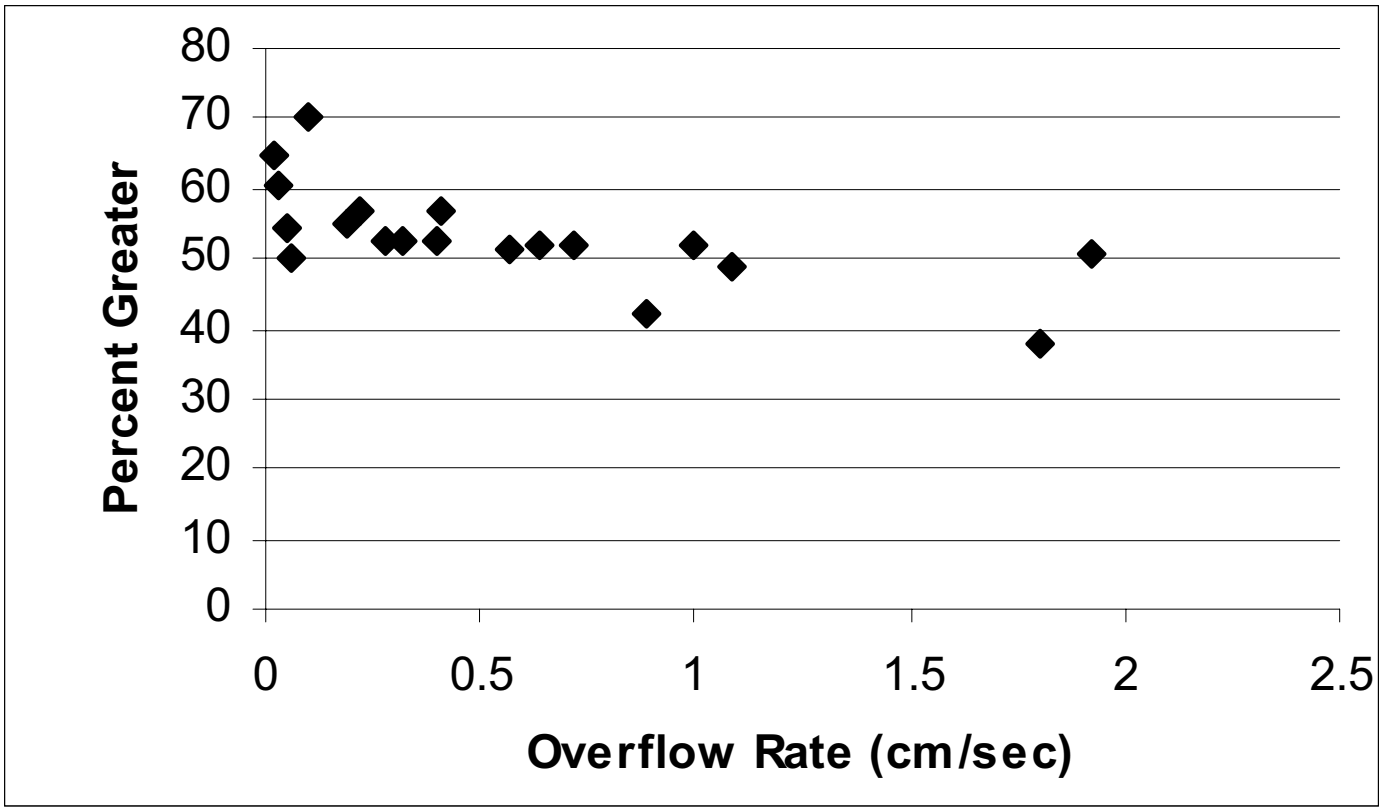


Figure C-2: Percent Removal versus Overflow Rate, Experiment 2, Long Column [36 cm, C/L, Mixture]

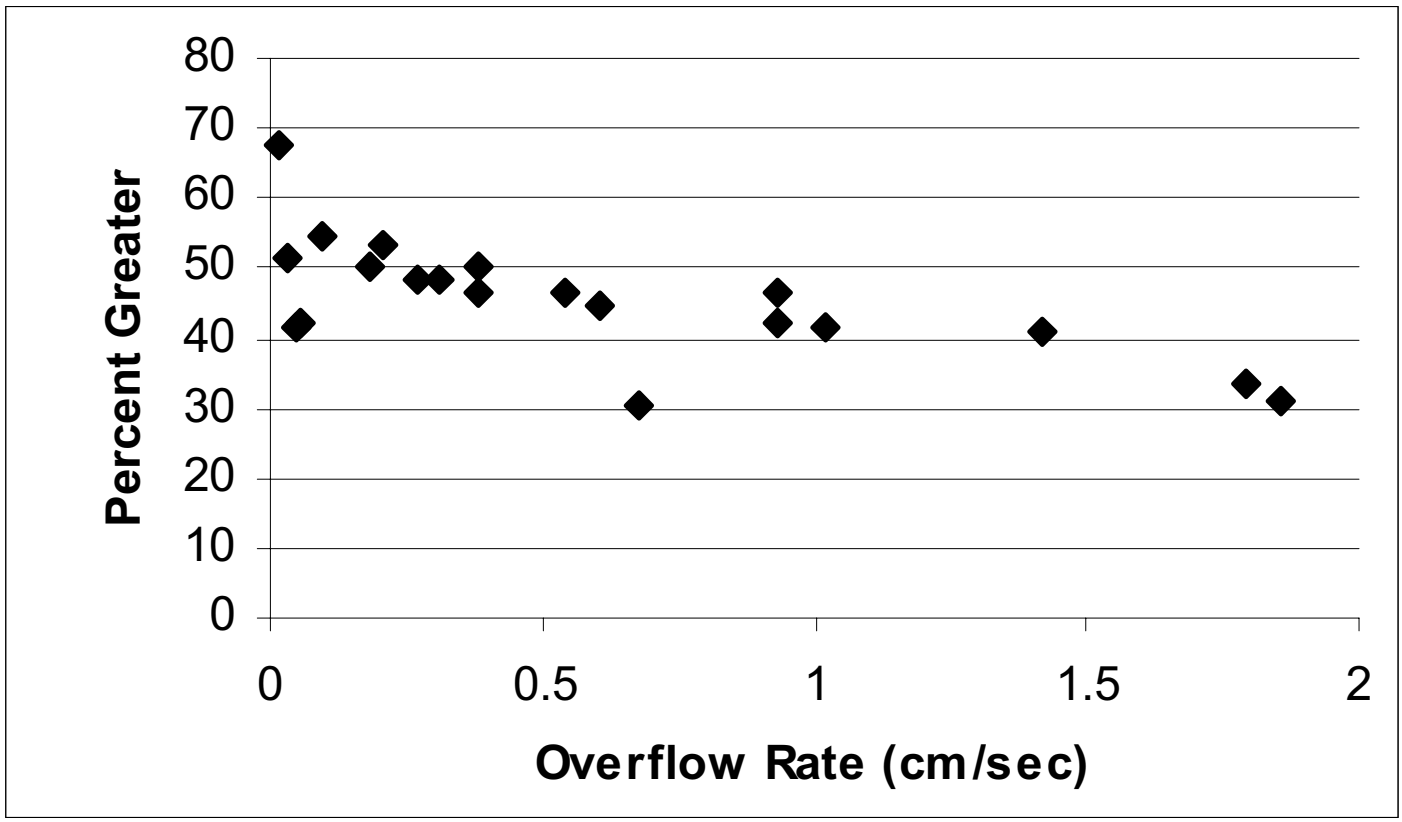


Figure C-3: Percent Removal versus Overflow Rate, Experiment 3, Long Column [18 cm, C/L, Mixture]

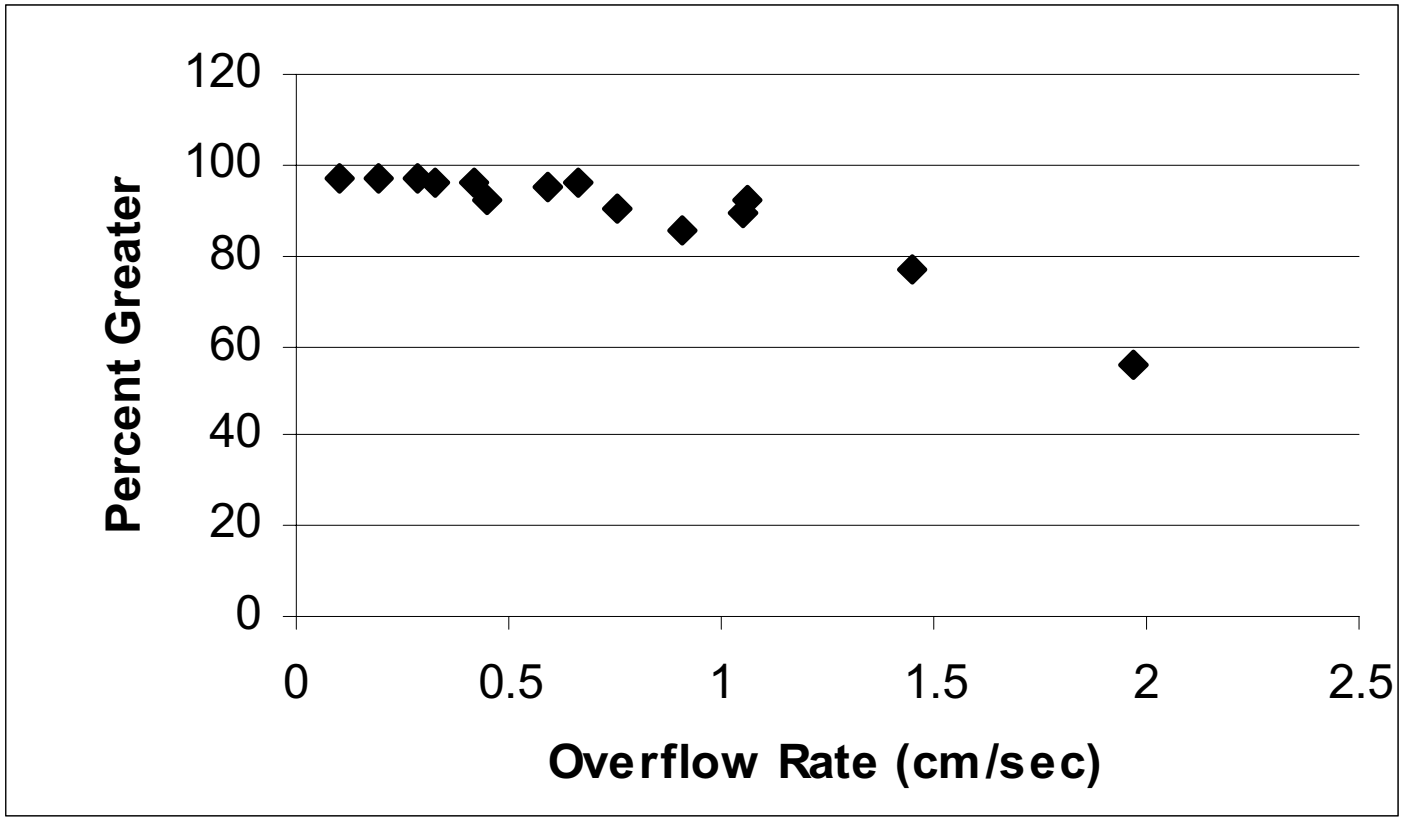


Figure C-4: Percent Removal versus Overflow Rate, Experiment 4, Long Column [18 cm, C/L, Microsand]

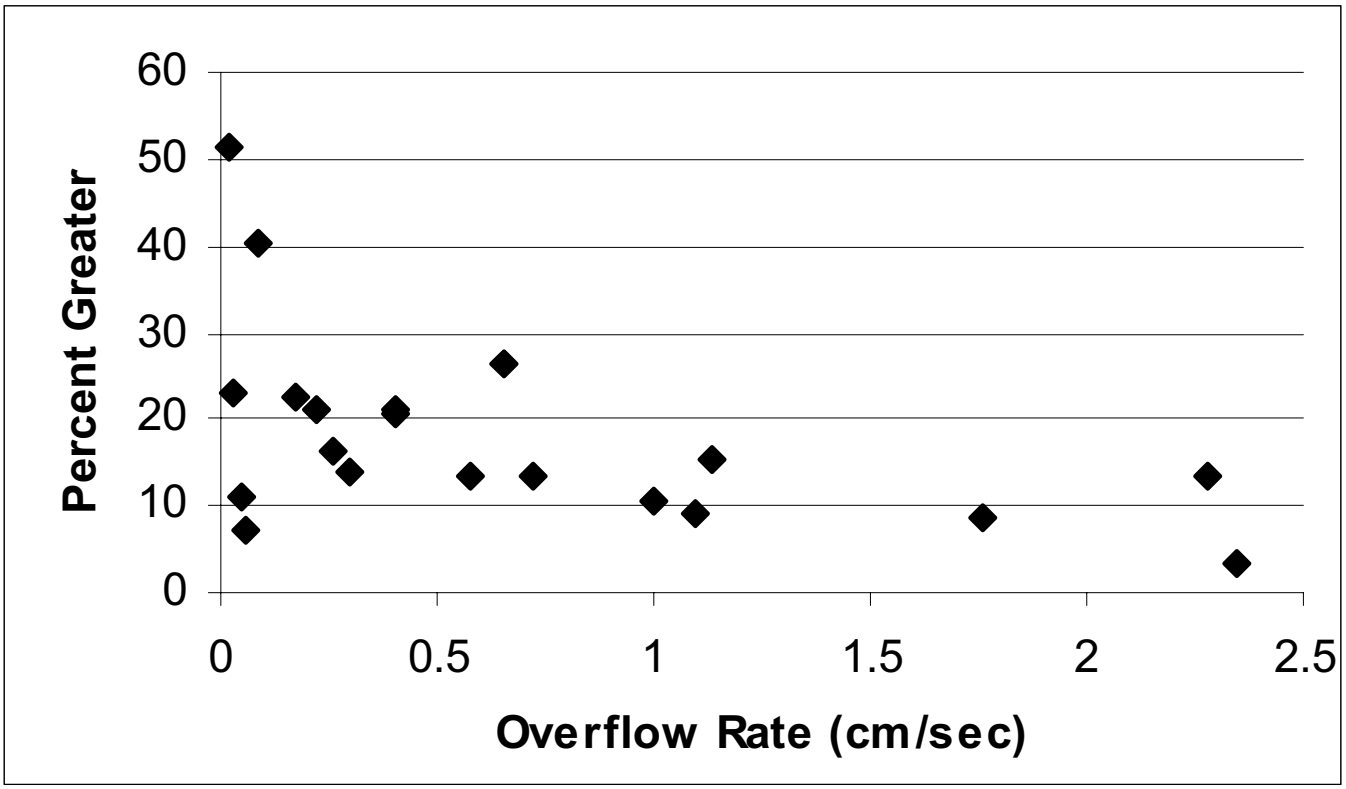


Figure C-5: Percent Removal versus Overflow Rate, Experiment 5, Long Column [18 cm, L/C, Neshaminy]

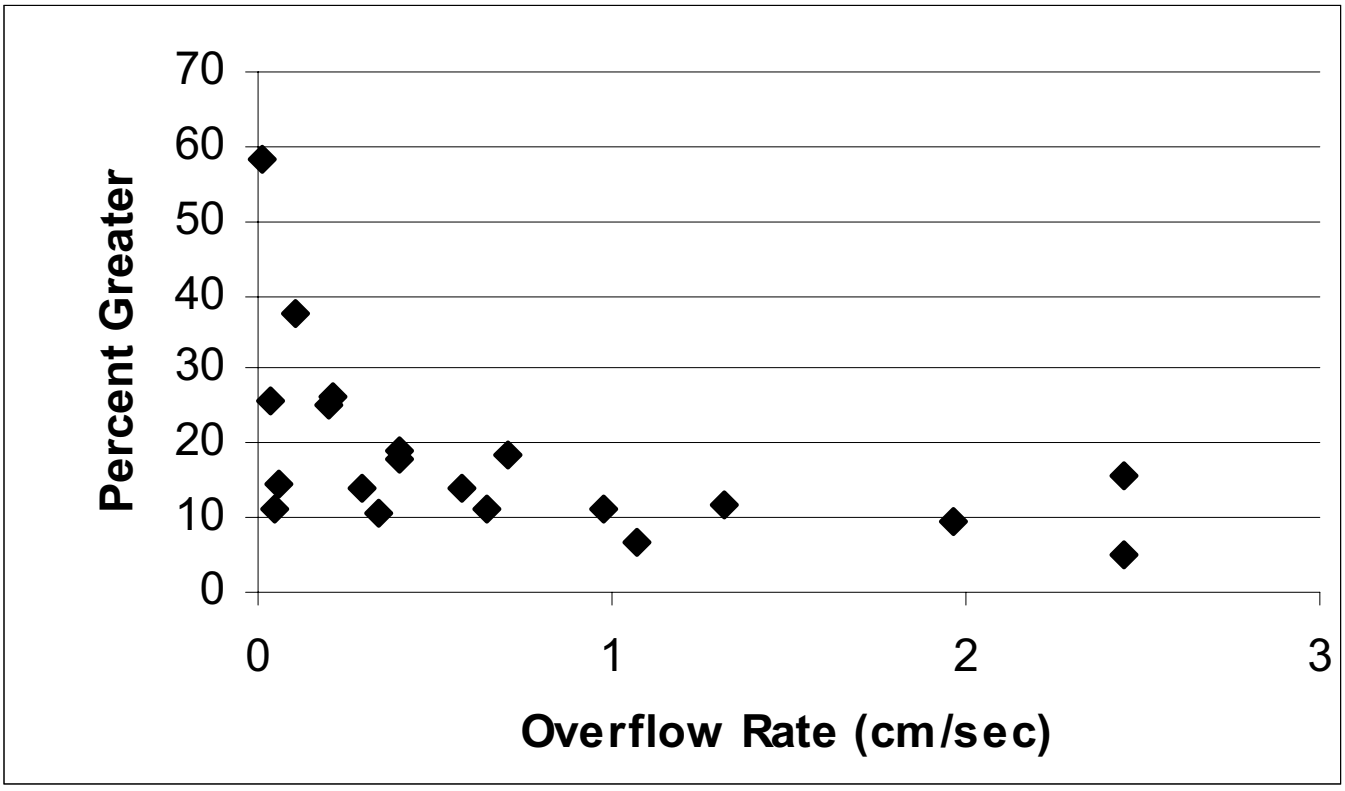


Figure C-6: Percent Removal versus Overflow Rate, Experiment 6, Long Column [36 cm, L/C, Neshaminy]

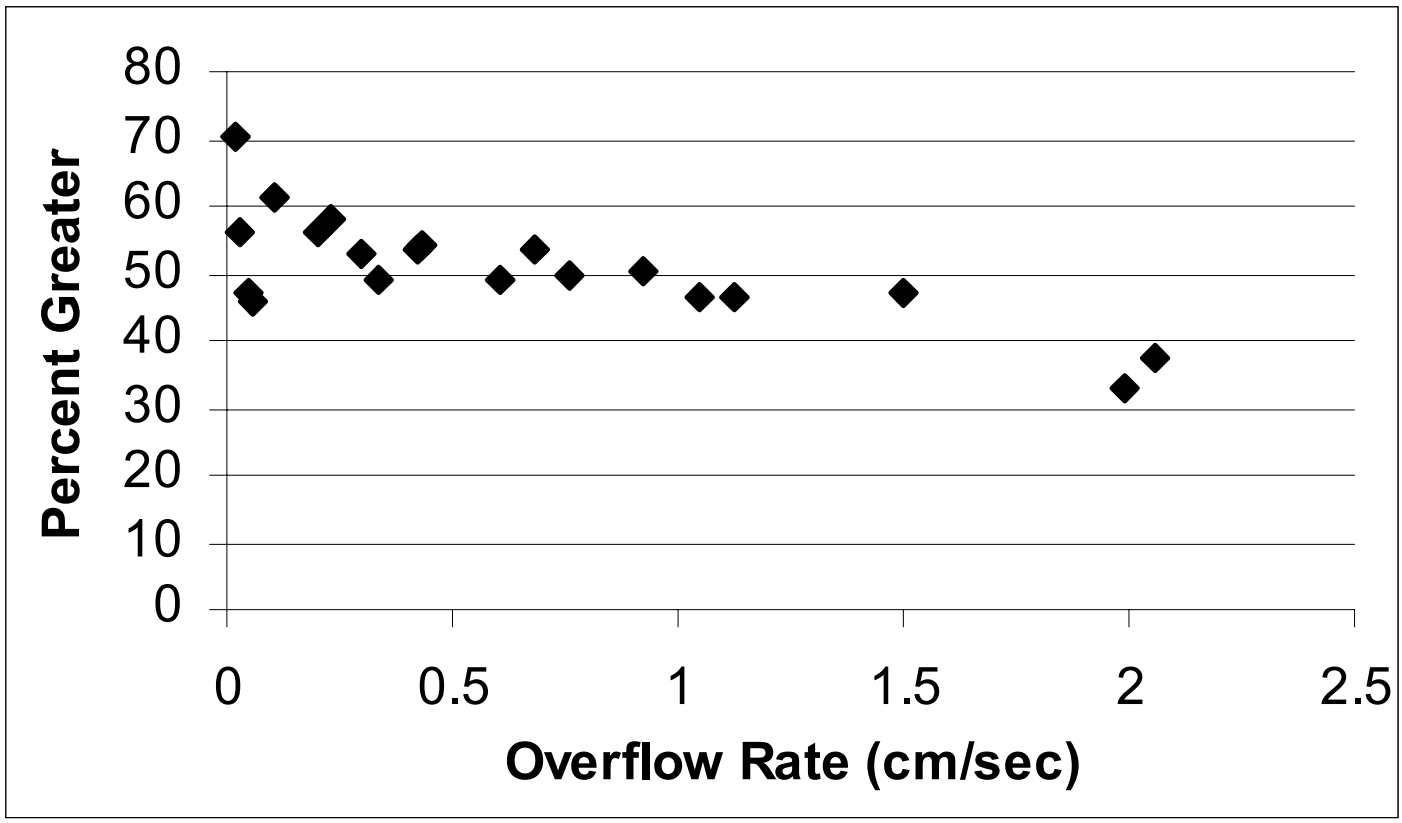


Figure C-7: Percent Removal versus Overflow Rate, Experiment 7, Long Column [18cm, C/L, Mixture]

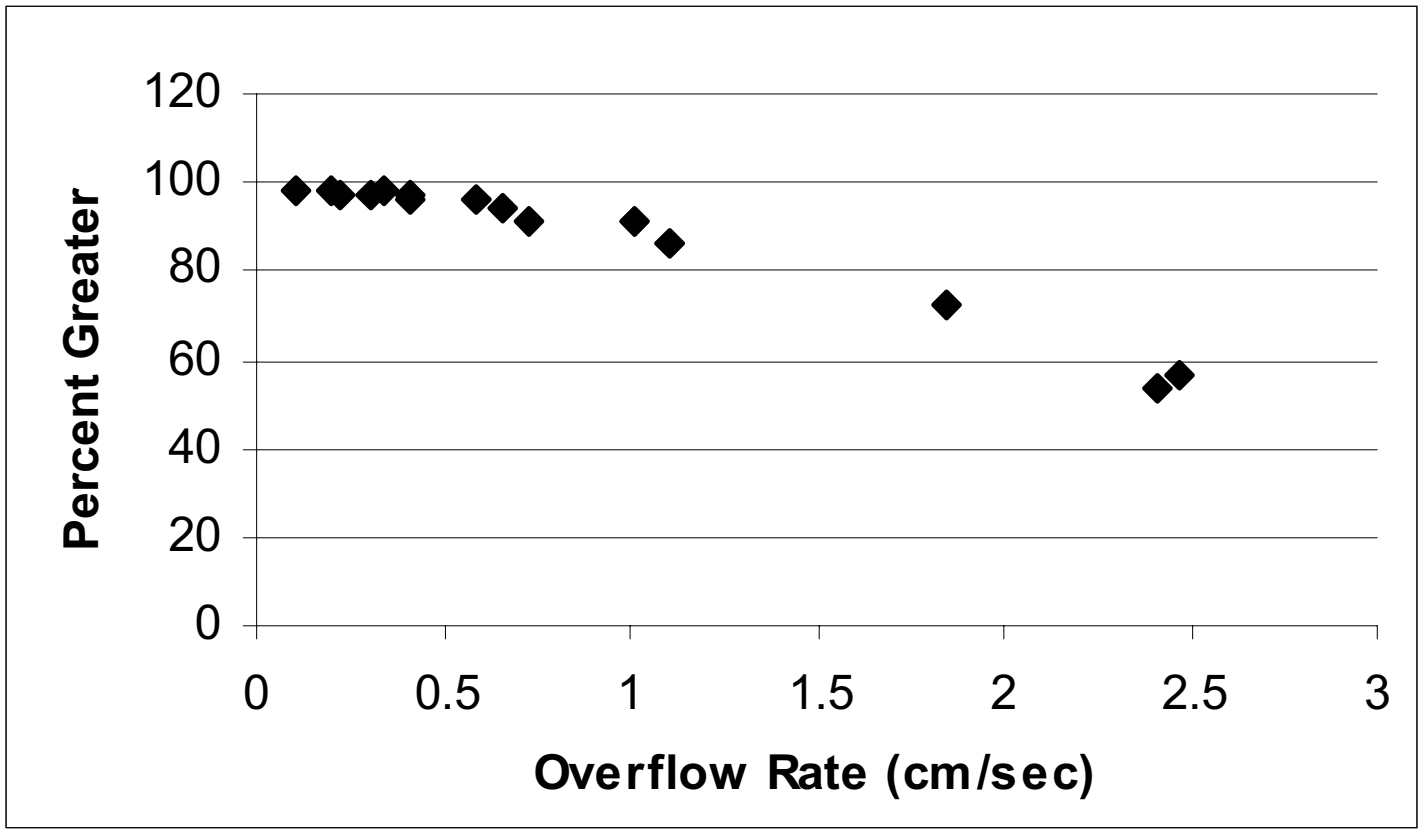


Figure C-8: Percent Removal versus Overflow Rate, Experiment 8, Long Column [18 cm, L/C, Microsand]

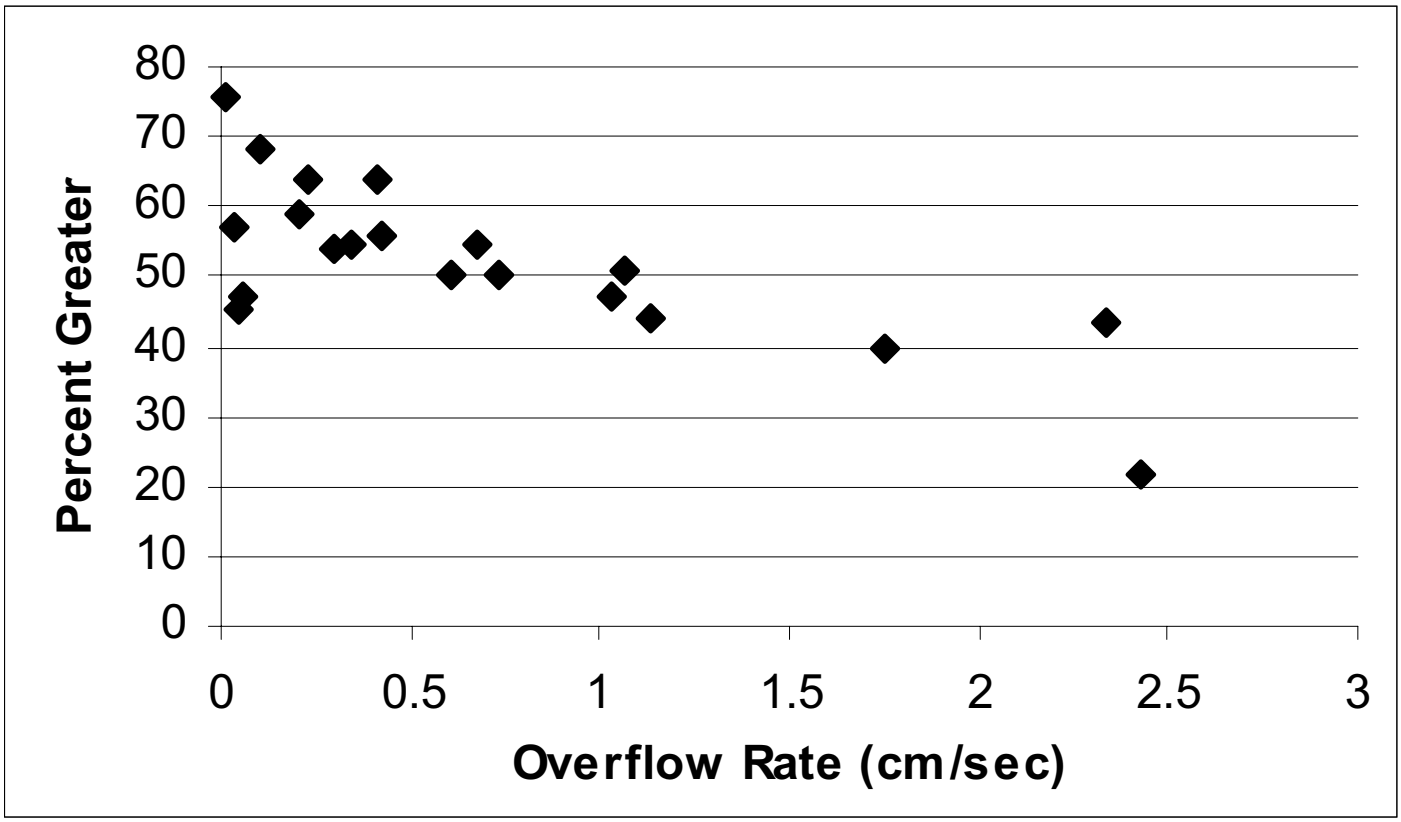


Figure C-9: Percent Removal versus Overflow Rate, Experiment 9, Long Column [18 cm, L/C, Mixture]

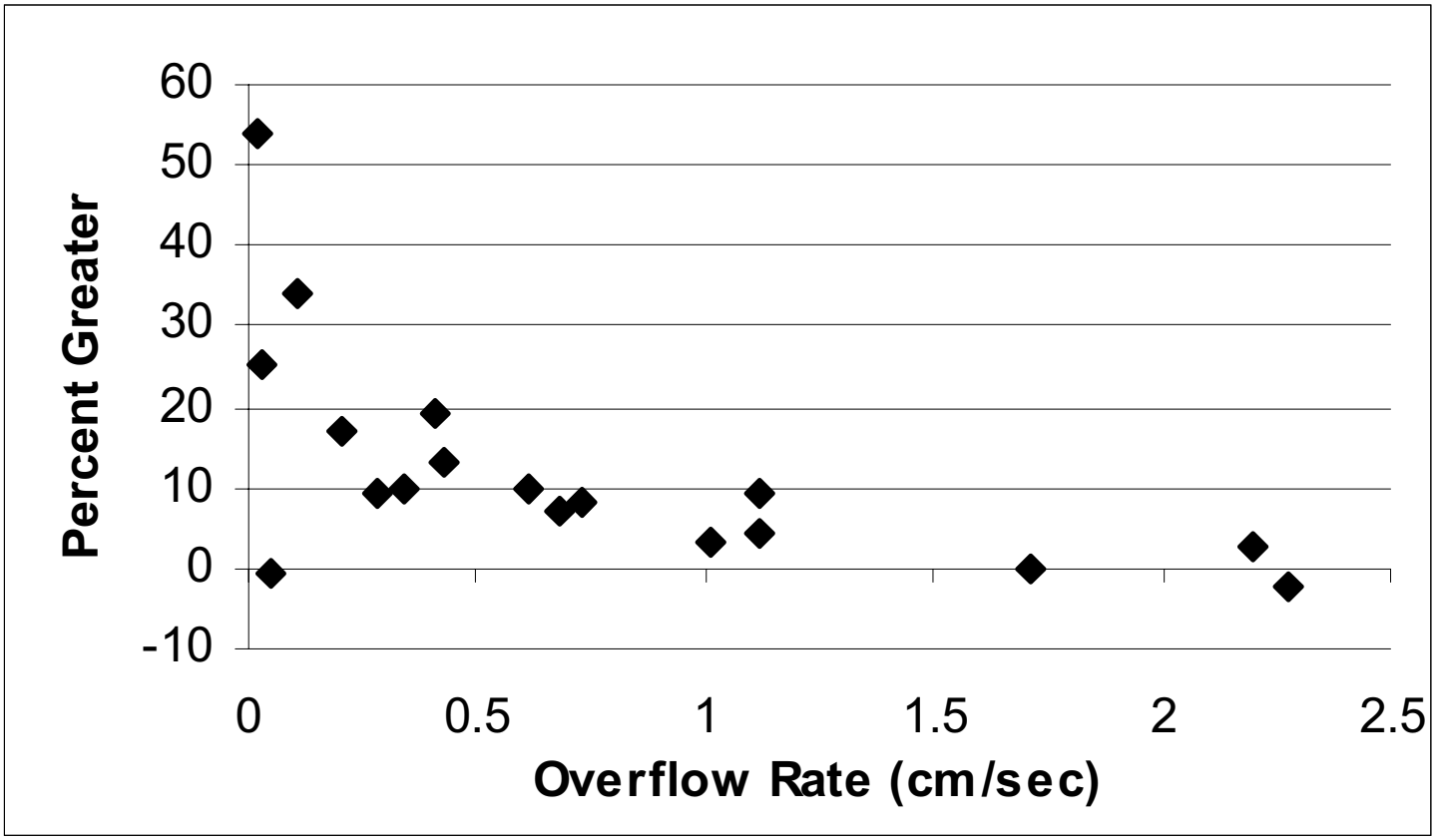


Figure C-10: Percent Removal versus Overflow Rate, Experiment 10, Long Column [36 cm, L/C, Neshaminy]

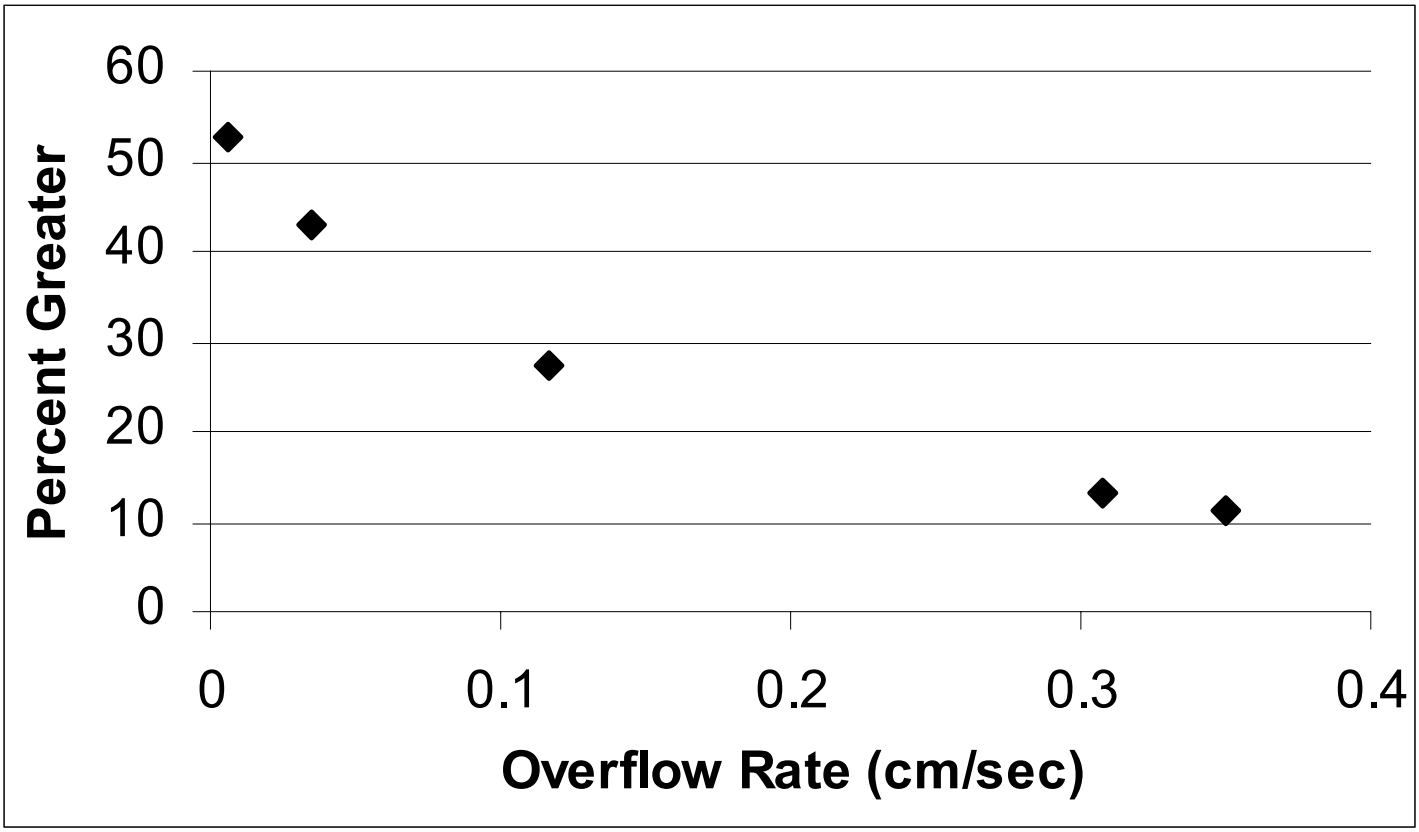


Figure C-11: Percent Removal versus Overflow Rate, Experiment 10, CERGRENE Column [36 cm, L/C, Neshaminy]

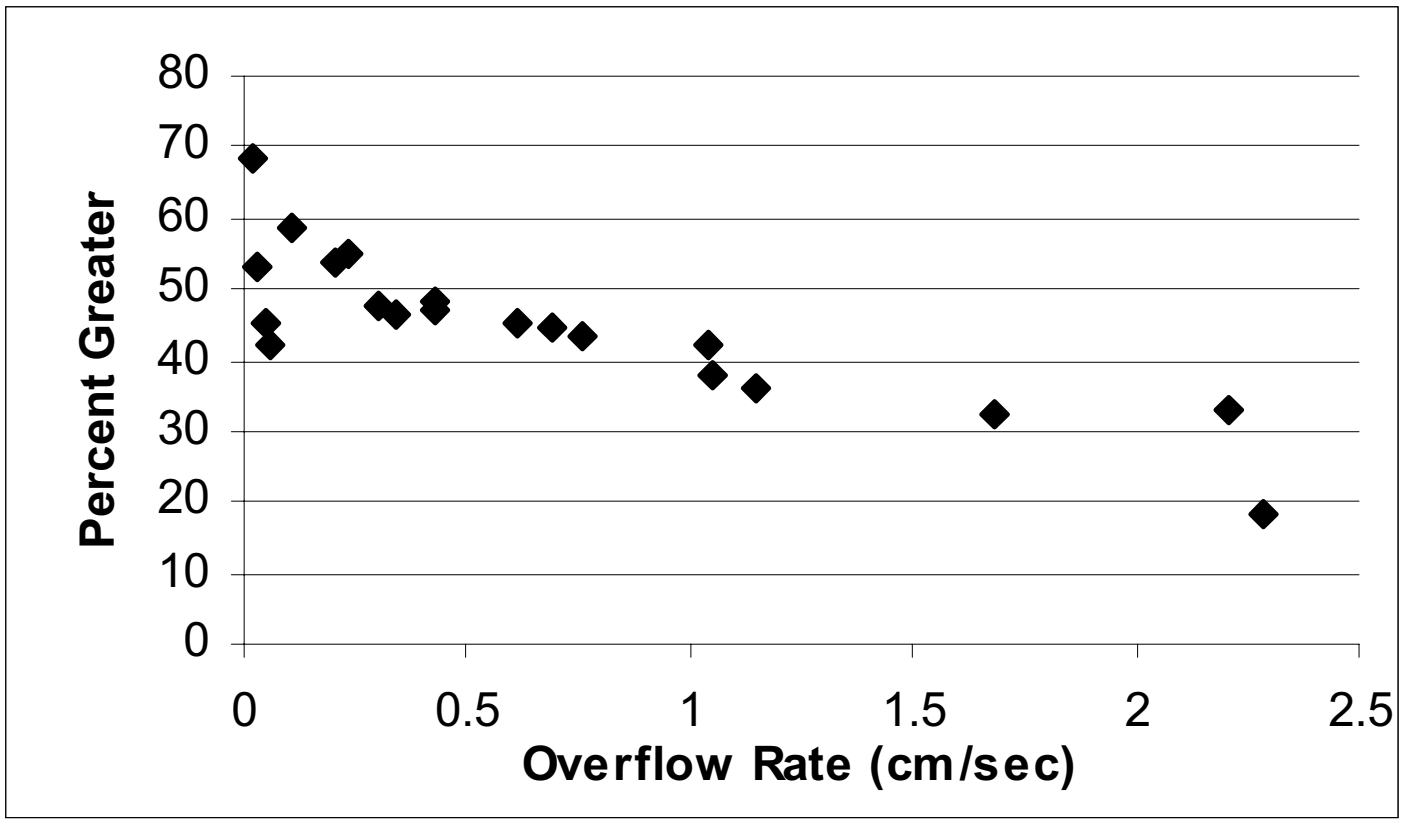


Figure C-12: Percent Removal versus Overflow Rate, Experiment 11, Long Column [36 cm, L/C, Mixture]

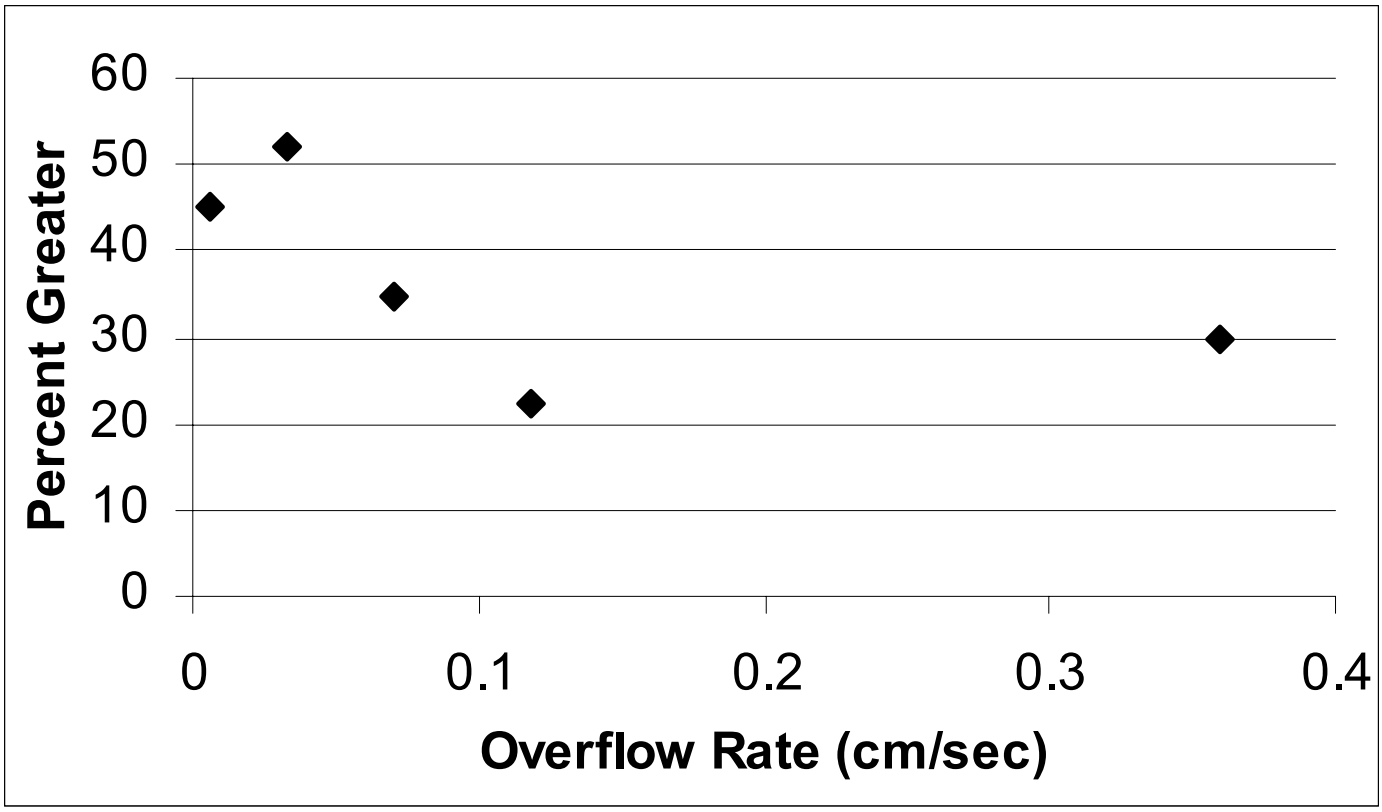


Figure C-13: Percent Removal versus Overflow Rate, Experiment 11, CERGRENE Column [36 cm, L/C, Mixture]

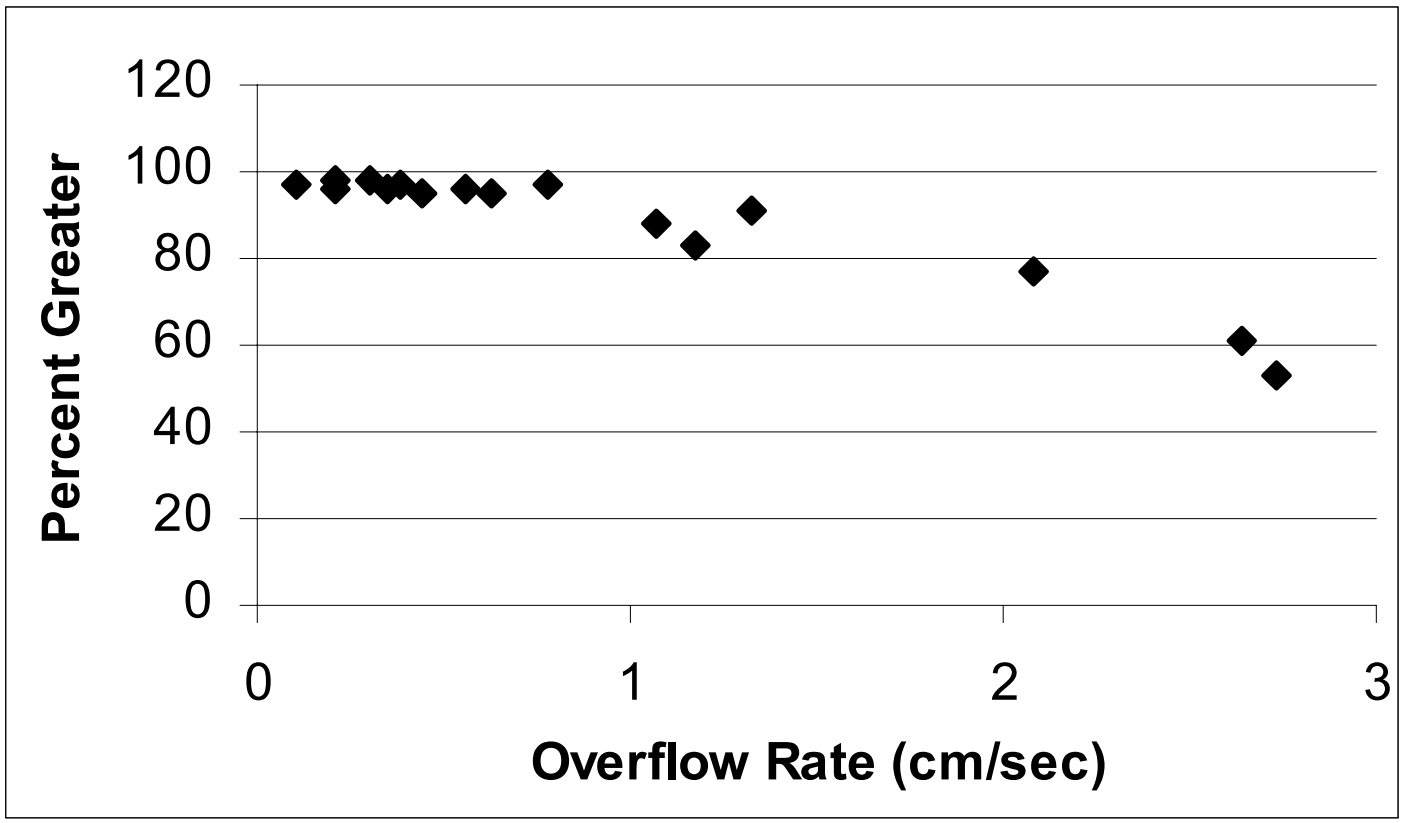


Figure C-14: Percent Removal versus Overflow Rate, Experiment 12, Long Column [18 cm, L/C, Microsand]

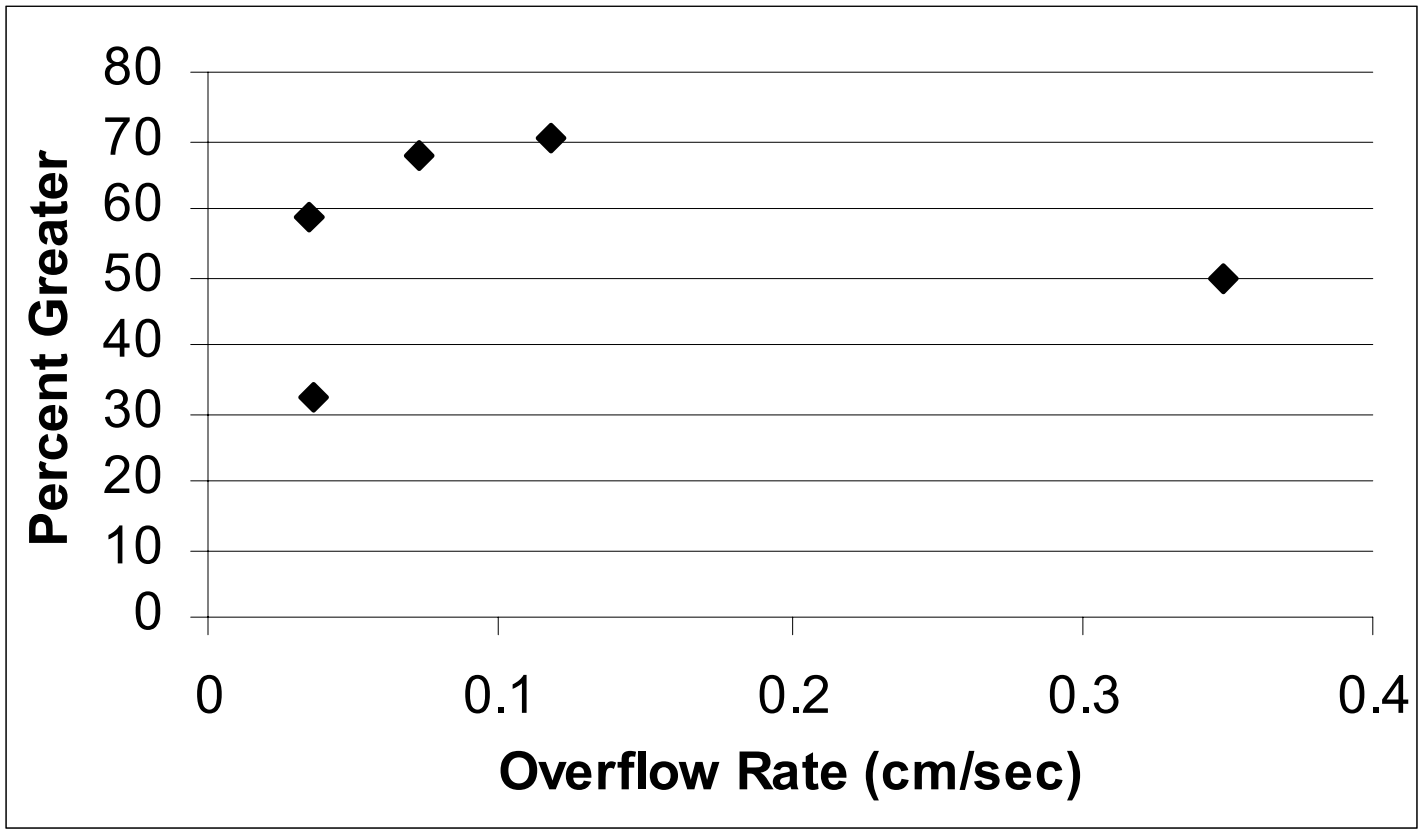


Figure C-15: Percent Removal versus Overflow Rate, Experiment 12, CERGRENE Column [18 cm, L/C, Microsand]

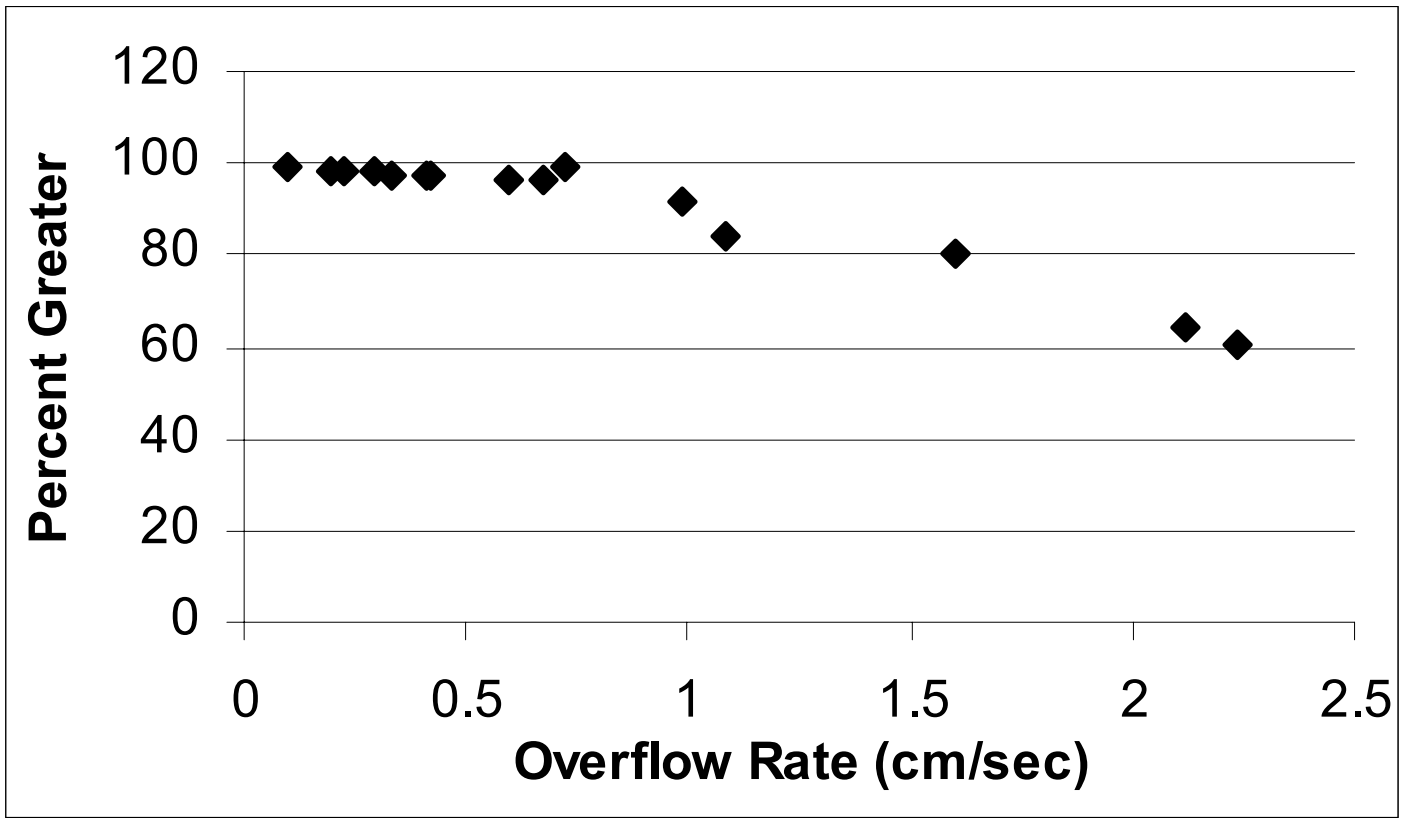


Figure C-16: Percent Removal versus Overflow Rate, Experiment 13, Long Column [36 cm, C/L, Microsand]

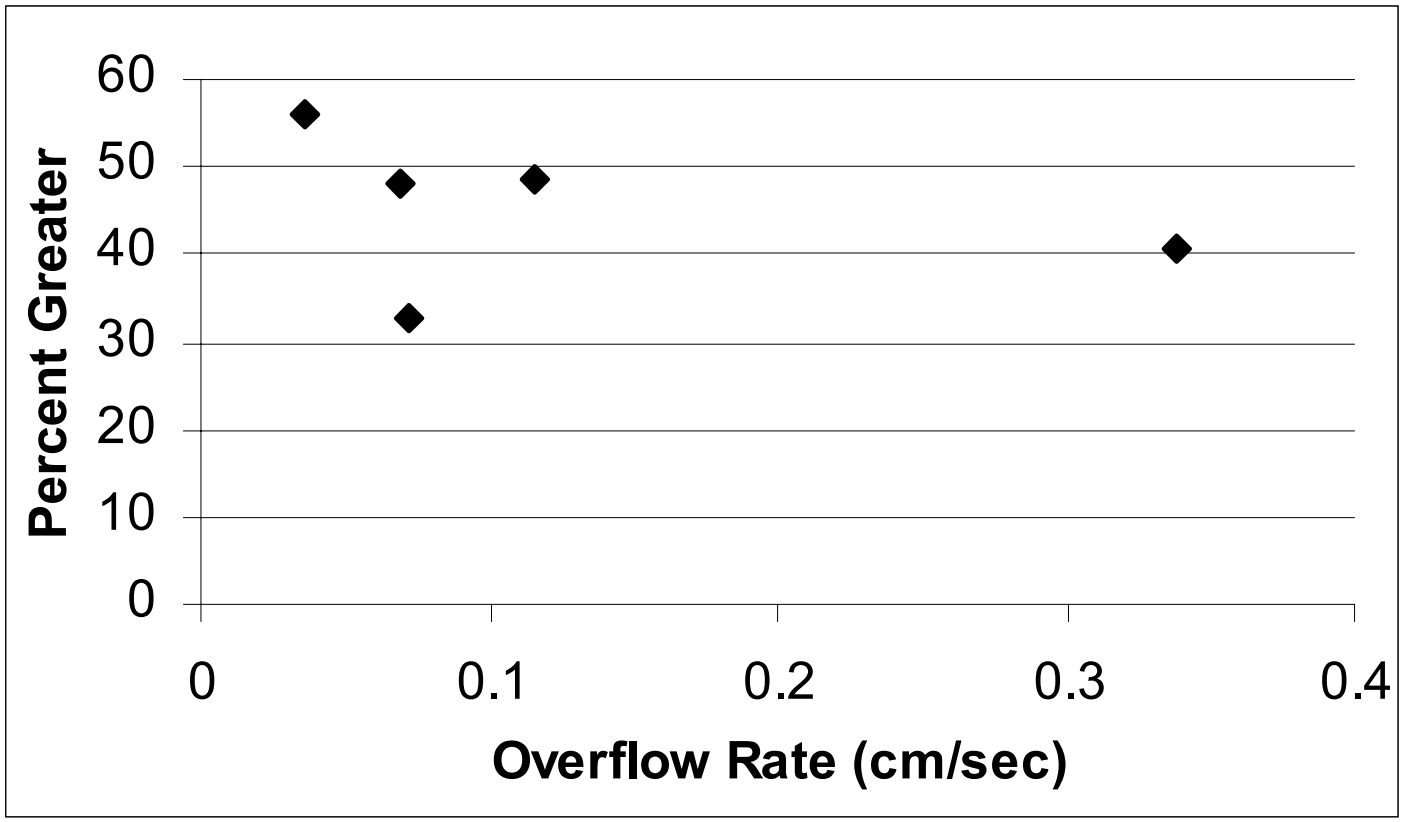


Figure C-17: Percent Removal versus Overflow Rate, Experiment 13, CERGRENE Column [36 cm, C/L, Microsand]

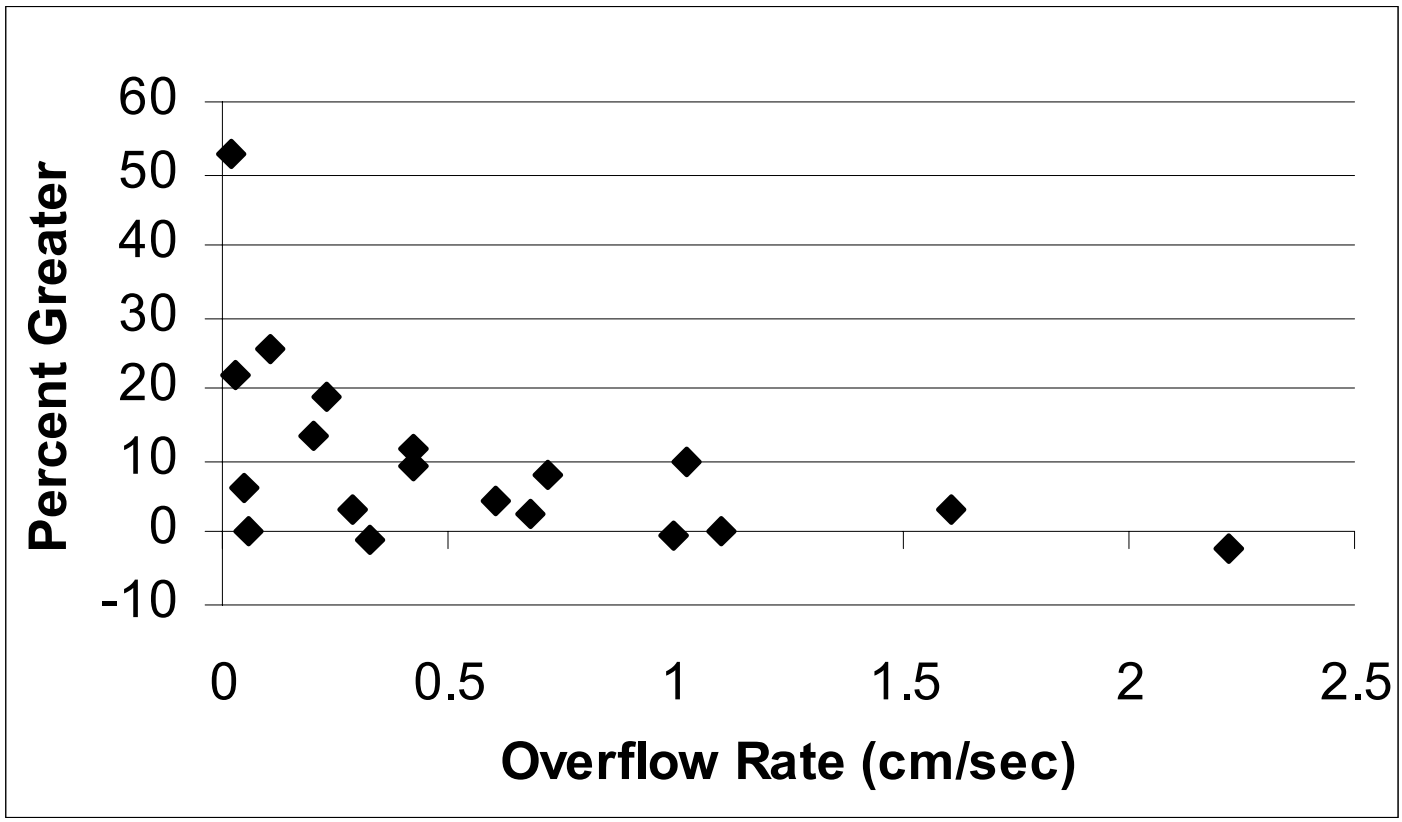


Figure C-18: Percent Removal versus Overflow Rate, Experiment 14, Long Column [18 cm, C/L, Neshaminy]

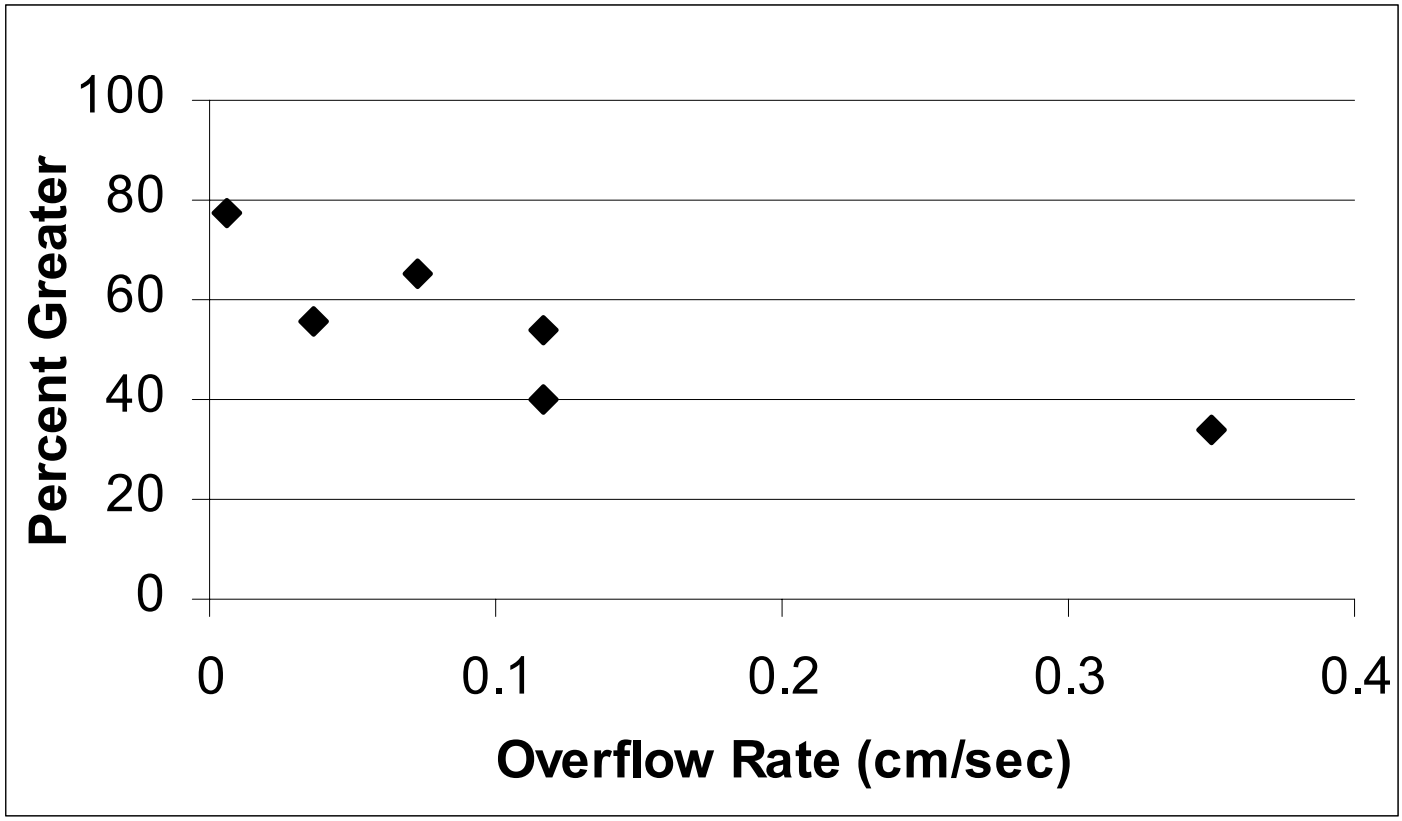


Figure C-19: Percent Removal versus Overflow Rate, Experiment 14, CERGRENE Column [18 cm, C/L, Neshaminy]

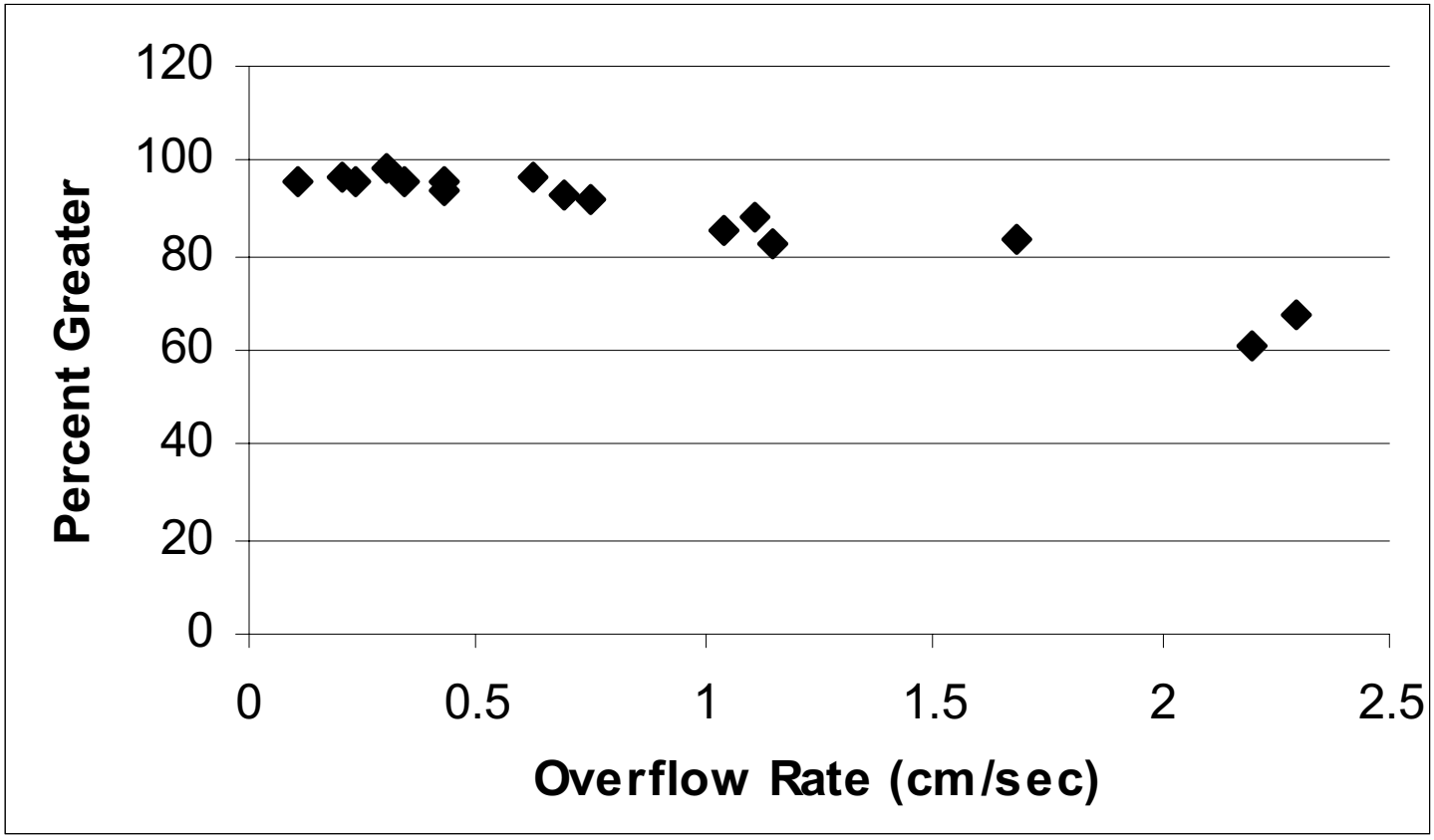


Figure C-20: Percent Removal versus Overflow Rate, Experiment 15, Long Column [36cm, L/C, Microsand]

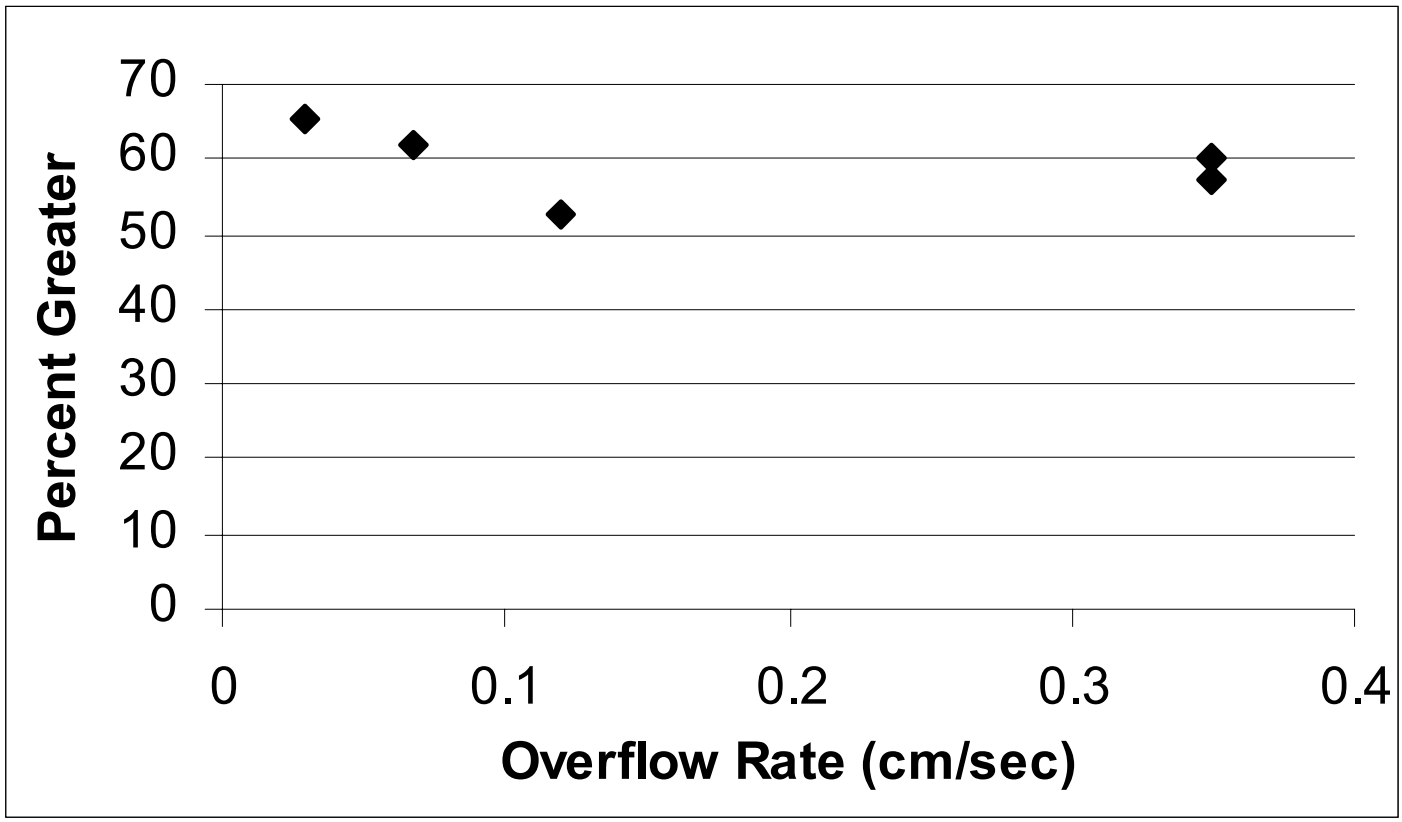


Figure C-21: Percent Removal versus Overflow Rate, Experiment 15, CERGRENE Column [36cm, L/C, Microsand]

Appendix D

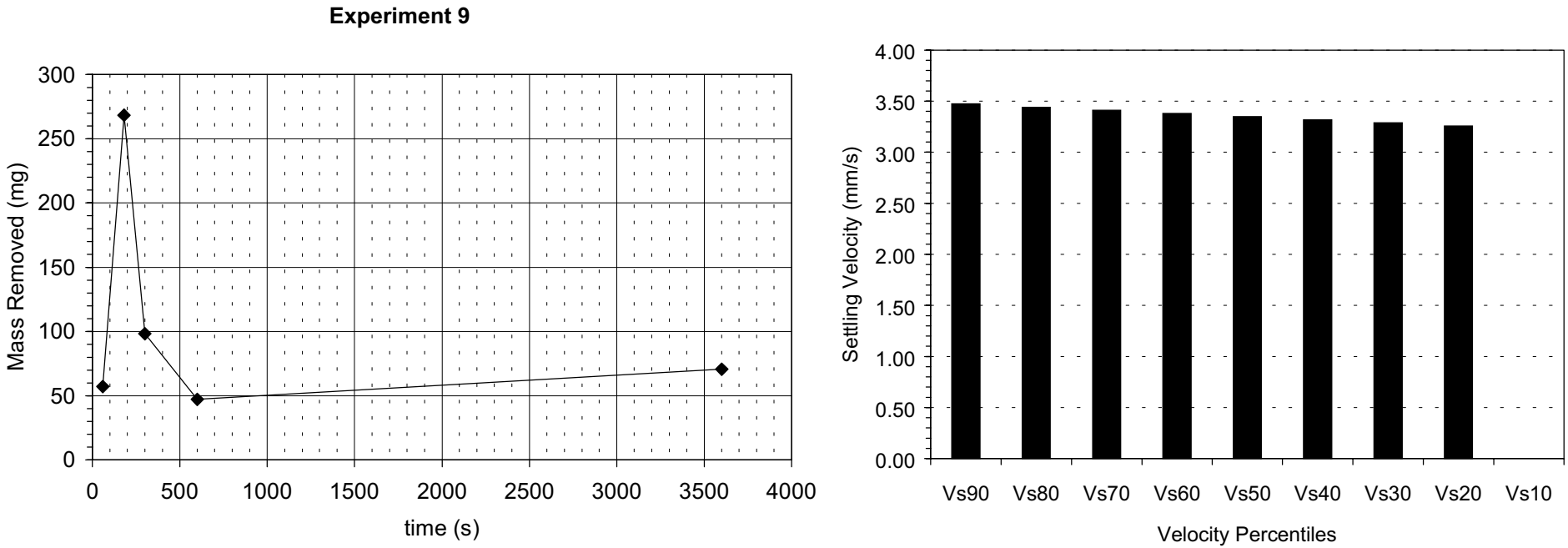


Figure D-1

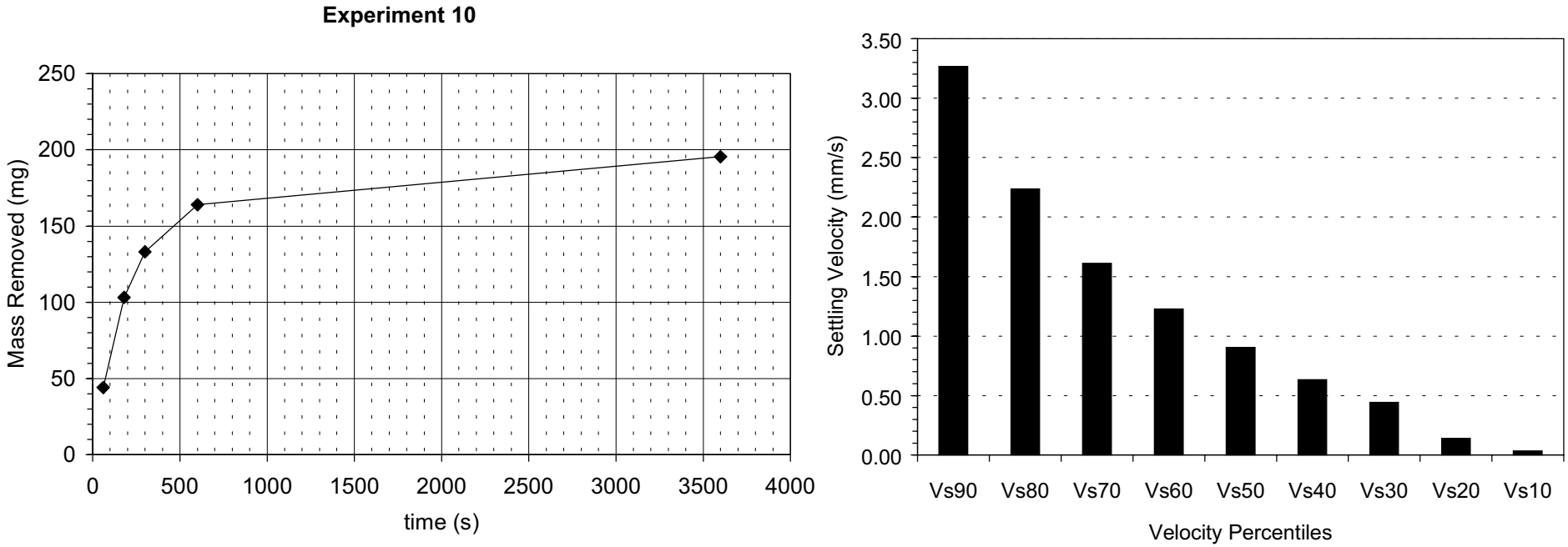
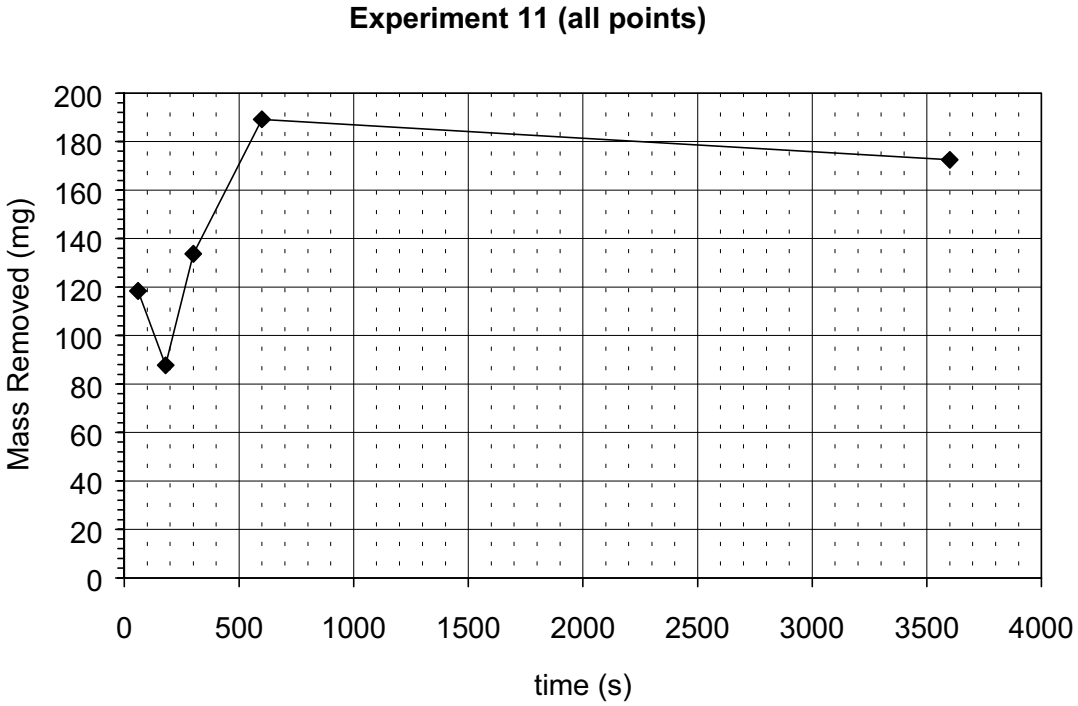


Figure D-2



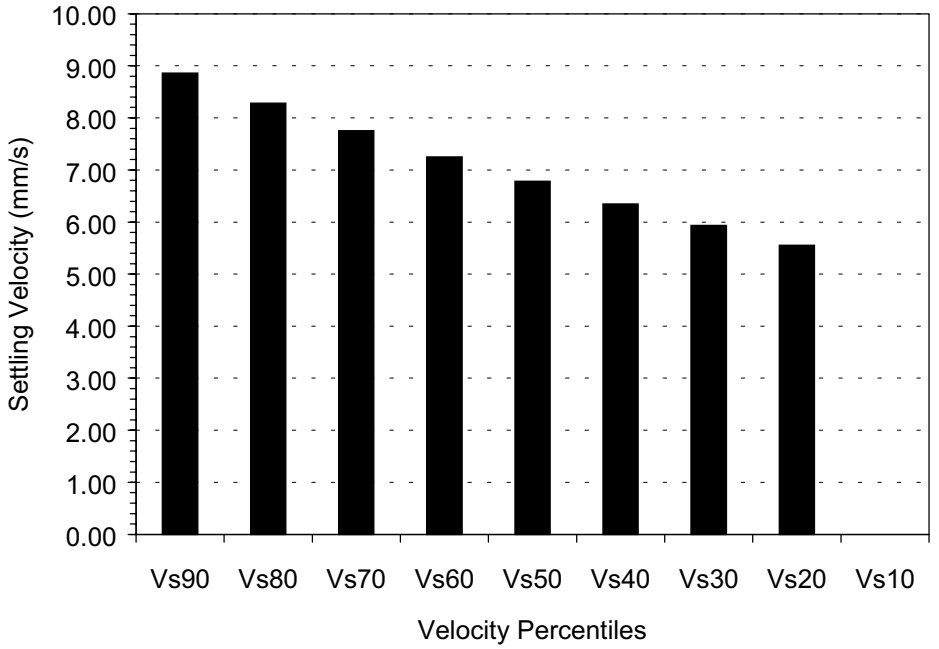
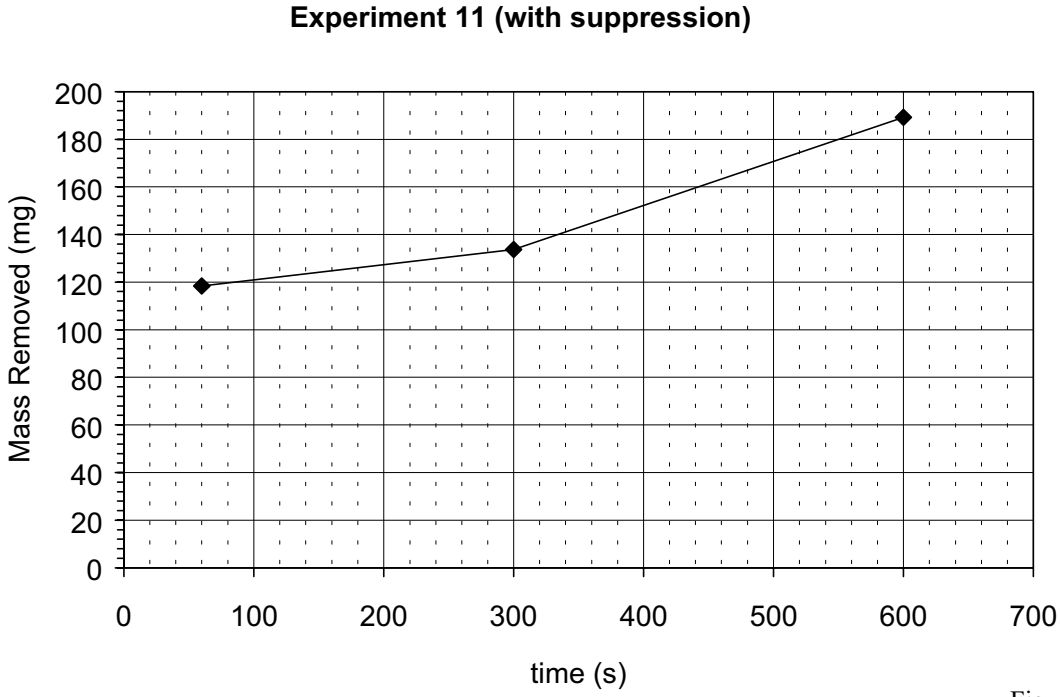


Figure D-3



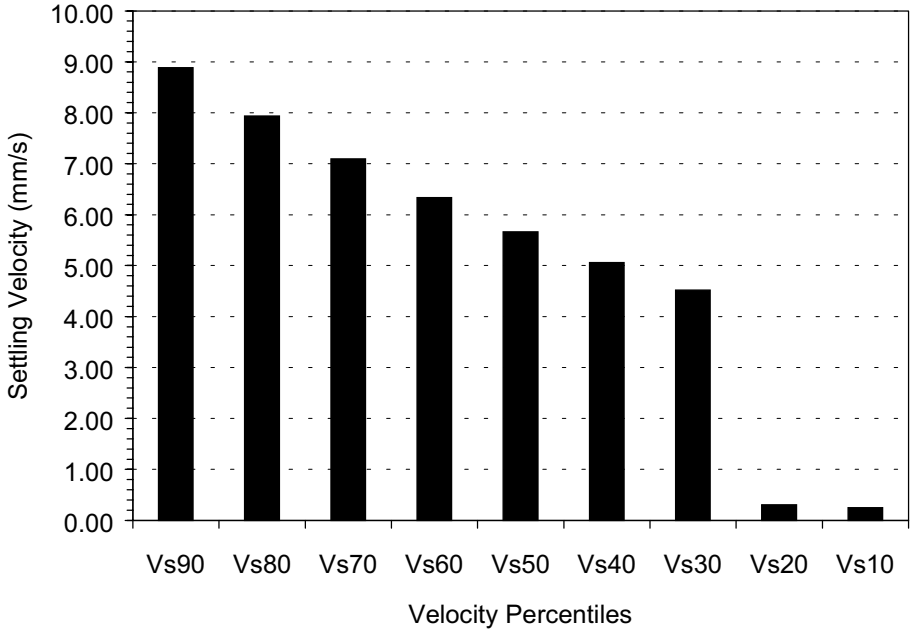


Figure D-4

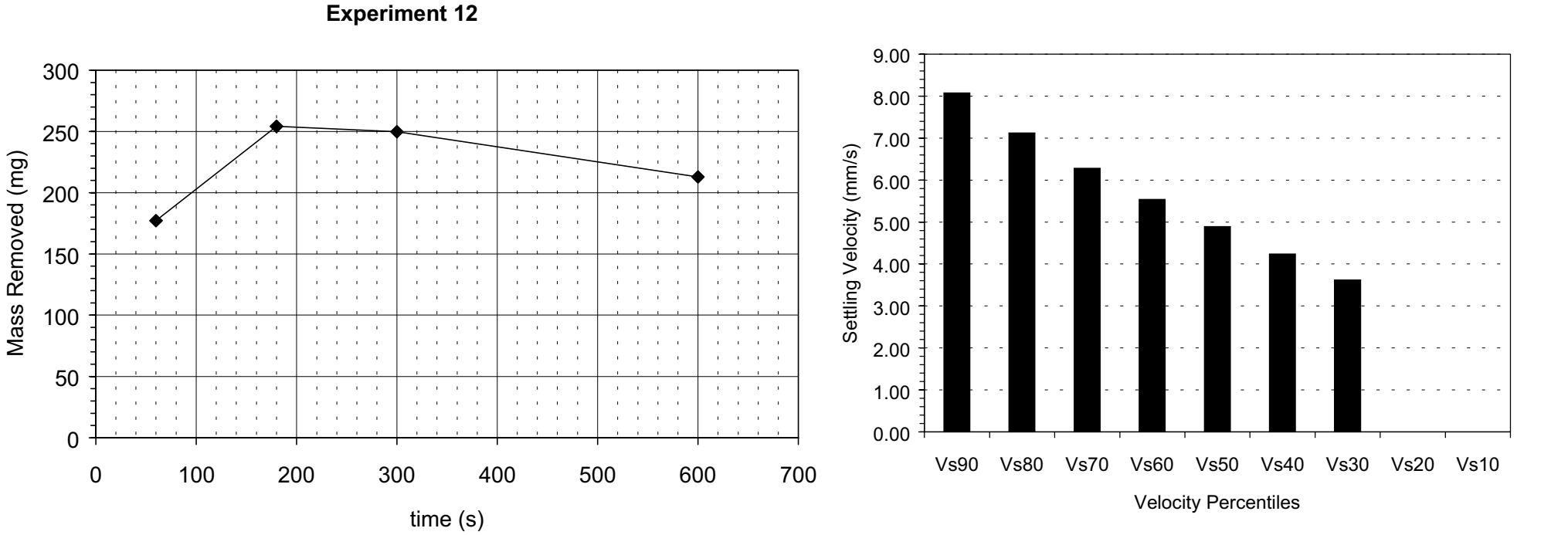


Figure D-5

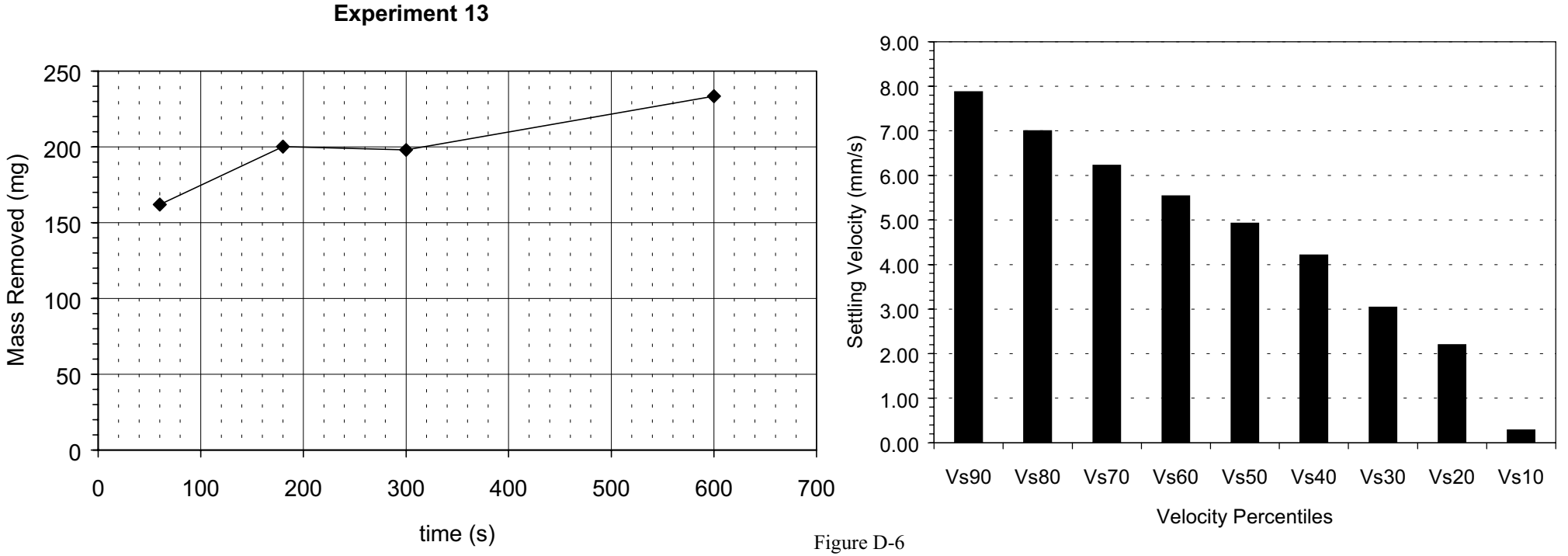
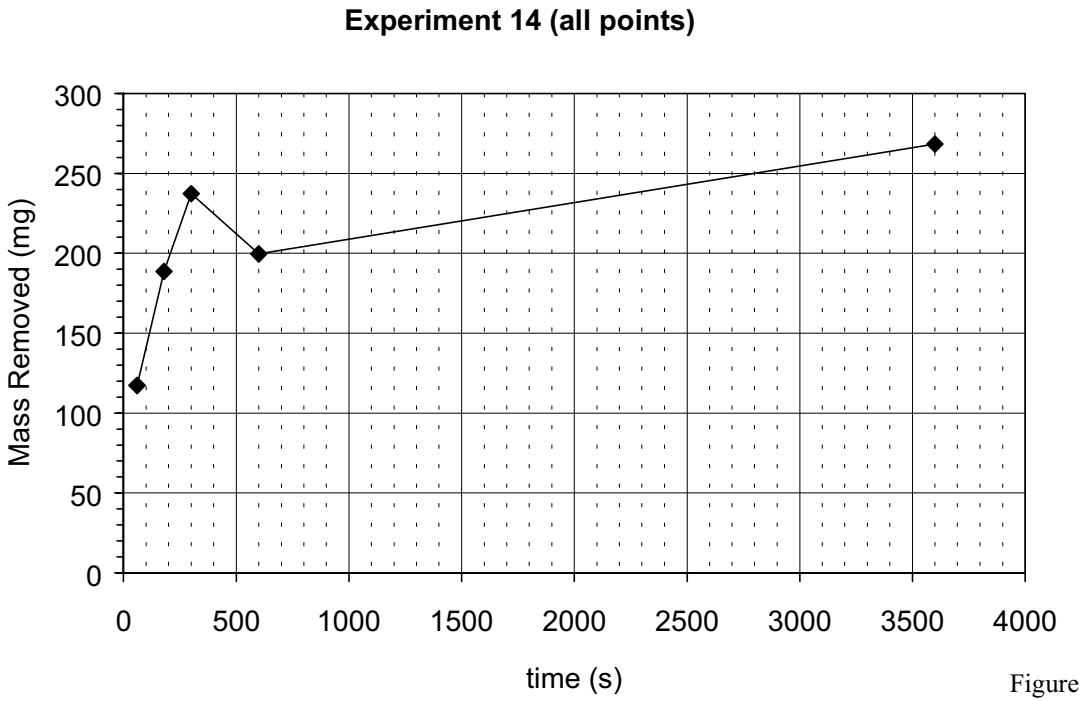


Figure D-6



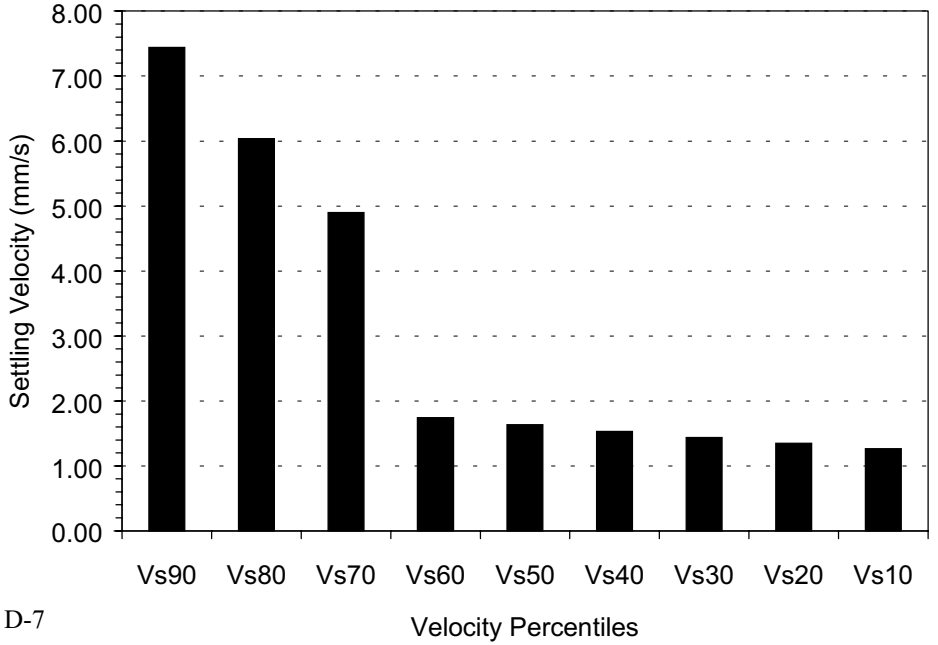
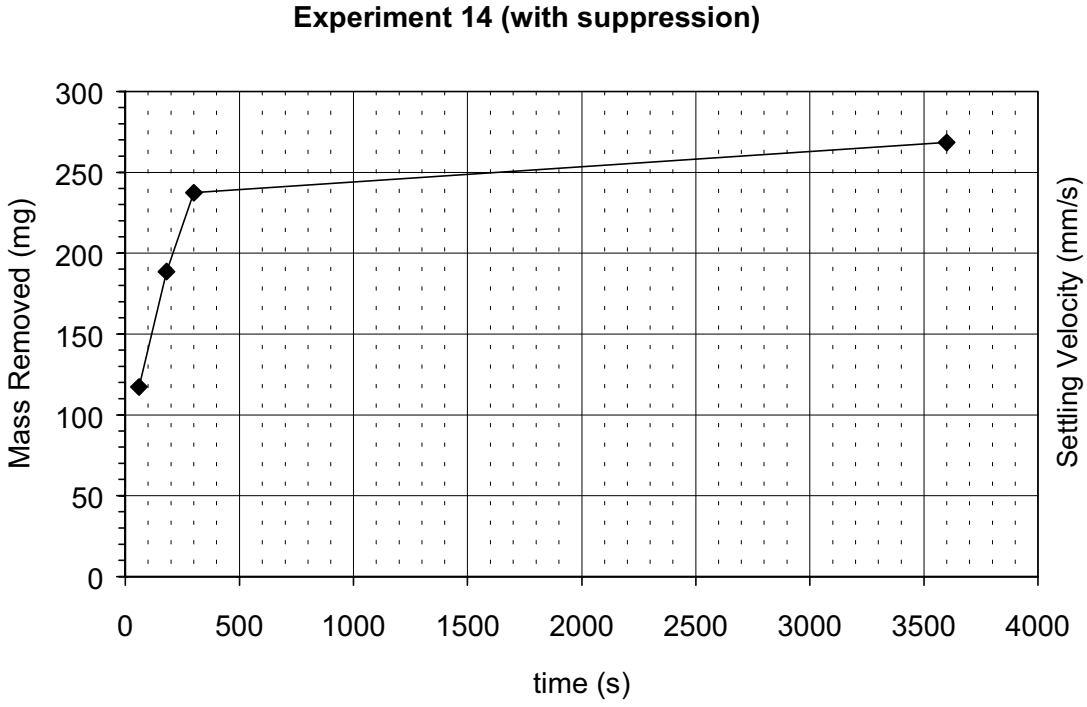


Figure D-7



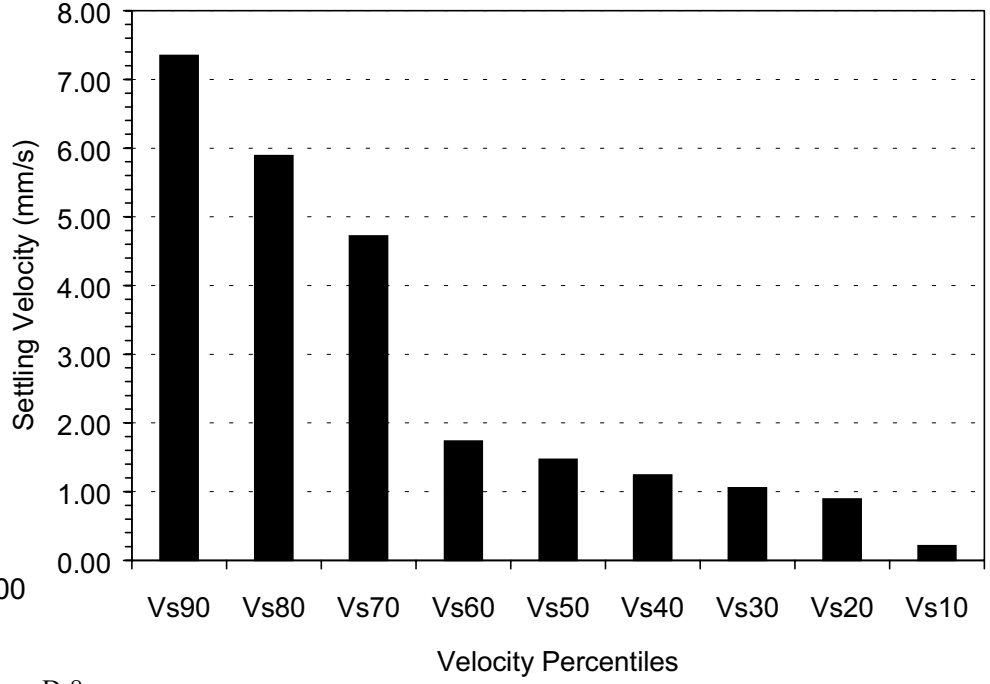
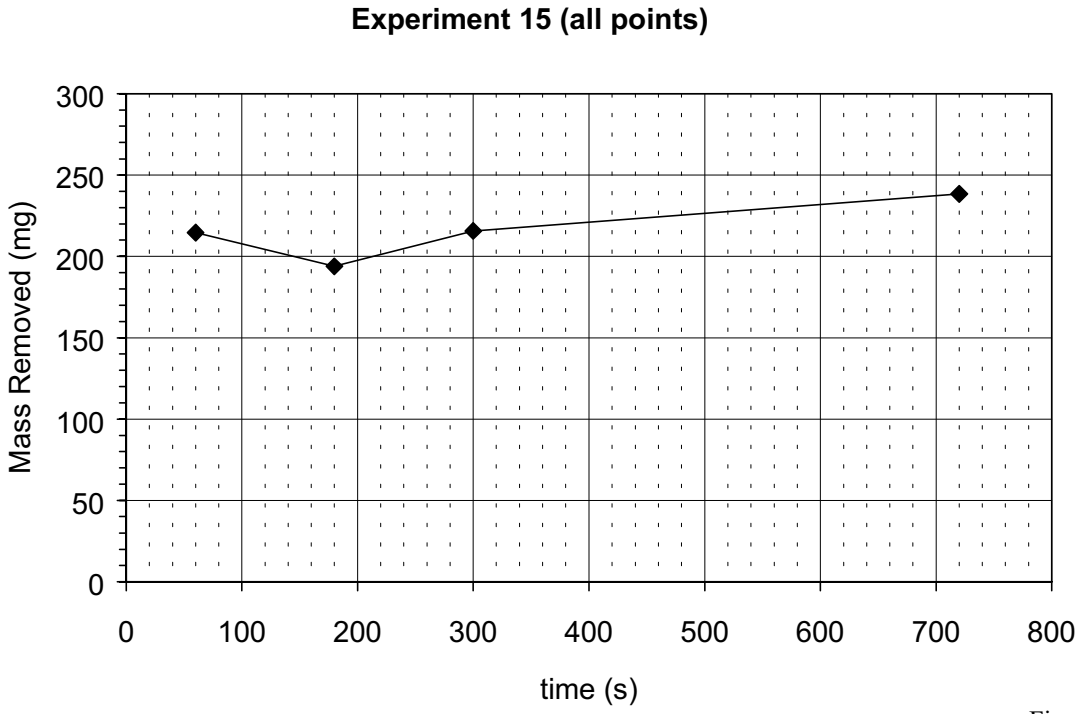


Figure D-8



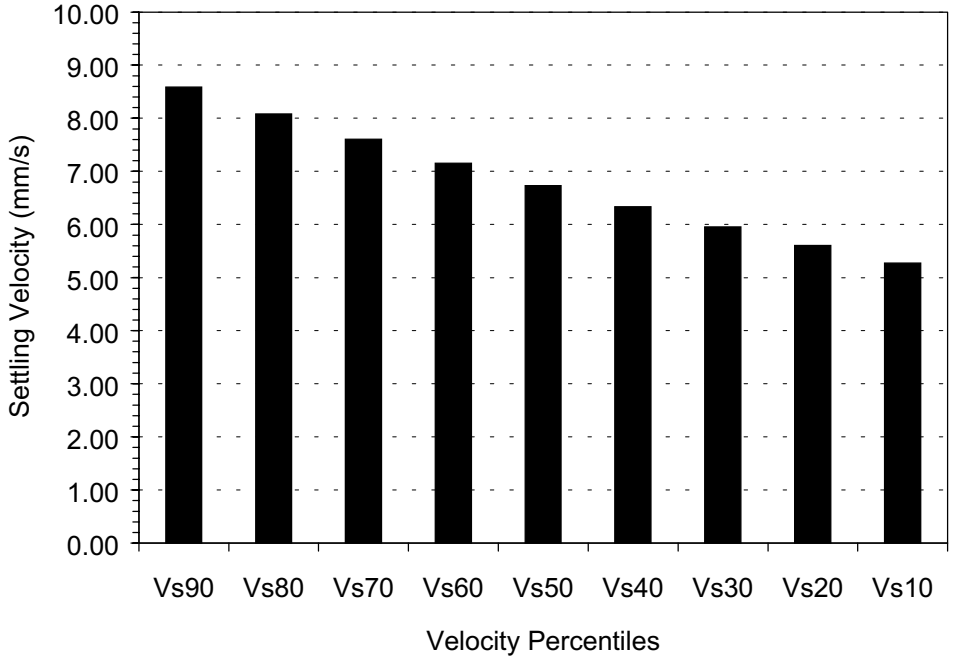
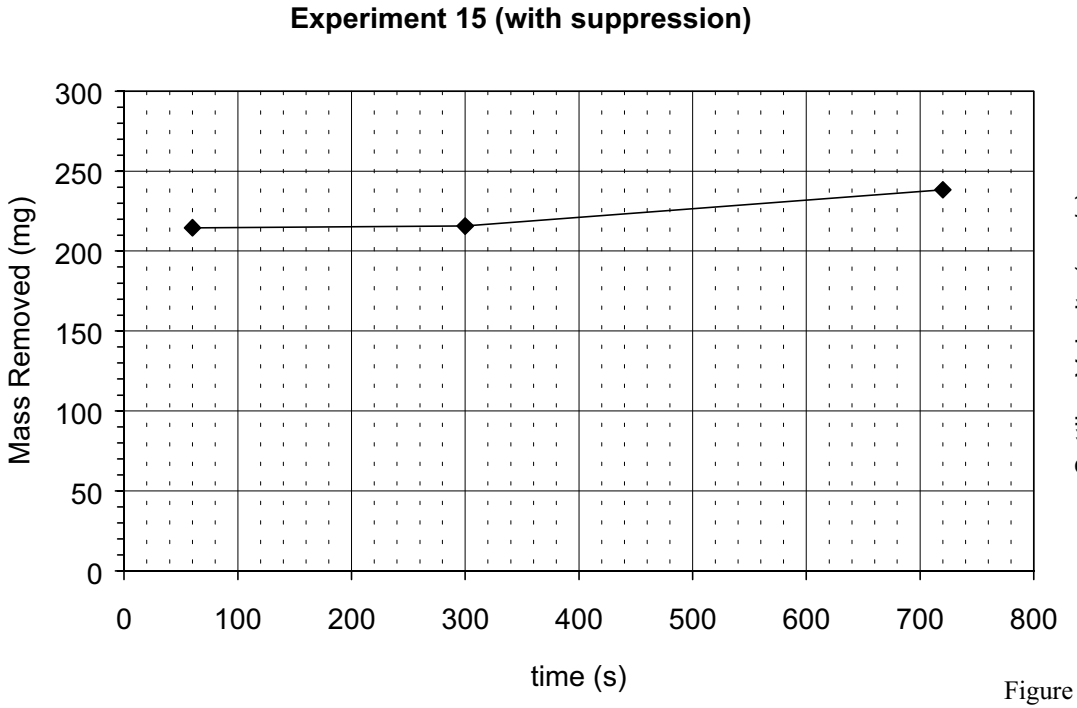


Figure D-9



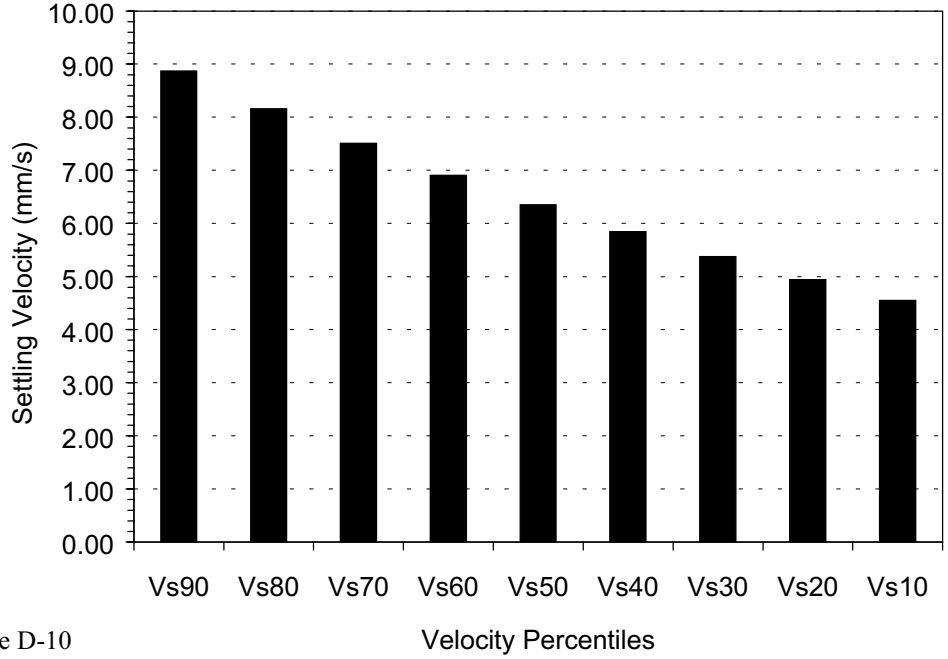


Figure D-10

Appendix E

CERGRENE Matrix Analysis

Each CERGRENE column has a top section and a bottom section which can be isolated by the central ball valve. The settling height (h) is measured from the top of the water level to the start of the bottom section. The initial mass of particles is introduced by vacuum aspiration into each column. If the mixing basin is homogeneous, the initial mass of solids (Moi) should be the same for columns i to (Nf-1), Nf being the total number of sampling points.

$$Mo_i = Mo \quad \forall i = 1 \; to \; (Nf - 1)$$

By noting, MH, the mass of particles in the top section and MB, the mass of particles in the bottom section, the following relation can be written:

$$Mo_i = MBo_i + MHo_i \quad \forall i = 1 \; to \; (Nf - 1)$$

Also, assuming the mixing is homogeneous, the top and bottom section should be of same initial mass

$$MBo_i = MBo \quad and \quad MHo_i = MHo \quad \forall i = 1 \; to \; (Nf - 1)$$

The settling height is noted h, if the columns are identical this value should be constant:

$$h_i = h \quad \forall i = 1 \; to \; (Nf - 1)$$

At time $t = 0$, the initial mass, MBo_i, in the bottom part of the column is equal to the initial mass, MHo_i, in the top section of the column. At any given time, t= t_i and for any column i, the central ball valve can isolate the top and bottom sections of the column. The mass of solids found in the bottom section correspond to the initial mass in the bottom MBo_i and a fraction of settled solids M_i from the top section MHo_i that effectively settled between times $t = 0$ and $t = t_i$.

$$MB_i = MBo_i + M_i \quad \forall i = 1 \; to \; (Nf - 1)$$

The accumulated masses from one column to the next, in function of time is given by :

$$MB_i - MB_{i-1} = MBo_i + M_i - MBo_{i-1} - M_{i-1} \quad \forall i = 1 \; to \; (Nf - 1)$$

Assuming an homogeneous mixing:

$$MB_i - MB_{i-1} = M_i - M_{i-1} = P_i \quad \forall i = 1 \; to \; (Nf - 1)$$

with P_i being the mass of the settled particles from the top section between time $t = t_{i-1}$ and $t = t_i$.

Thus

$$MB_i = MBo + M_i = MBo + \sum_{k=1}^{i} P_k \quad \forall i = 1 \; to \; (Nf - 1)$$

The accumulated mass becomes:

$$M_i = \sum_{k=1}^{i} P_k \quad \forall i = 1 \; to \; (Nf - 1)$$

Chebbo et al. (1992) analyzed this curve in the following fashion :

$$M(t) = S(t) + t\frac{dM(t)}{dt}$$

where

$M(t)$	cumulated mass of settled particles between $t = 0$ et t
$S(t)$	settled particles at time t with a settling velocity greater than $\frac{h}{t}$
$t\frac{dM(t)}{dt}$	mass of settled particles at time t with a settling velocity less than $\frac{h}{t}$

Appendix F

Experiment 1: 6/9/98 Long Column Initial Height=7'10"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.60	256.18
5	0.88	292.00
7	1.15	289.96
8	1.42	327.84
3	1.85	274.73
5	2.12	268.69
7	2.42	n/a
8	2.70	284.58
3	3.10	258.20
5	3.18	267.41
7	3.58	276.89
8	3.90	268.18
3	5.18	244.80
5	5.37	275.37
7	5.73	255.81
8	6.08	255.69
3	10.38	224.23
5	10.78	269.03
7	11.08	268.90
8	11.37	n/a
3	58.83	171.98
5	59.17	295.51
7	59.45	324.40
8	59.78	305.68

Blank Conc (mg/l)

3.03

Recycle Conc (mg/l)

1	267.14
2	267.97
3	265.20

Non-Settleable Solids (mg/l)

1	85.20
2	71.54

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	16.25	276.47
2	1.00	16.25	338.74
3	3.00	16.38	420.00
4	5.00	16.88	357.85
1	10.00	17.00	447.08
2	60.00	15.25	379.43
3	14.67	16.75	365.56

Experiment 2: 6/10/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.42	168.01
5	0.68	183.27
7	0.85	254.47
8	1.03	280.40
3	1.38	172.03
5	1.57	n/a
7	1.78	185.02
8	1.93	145.87
3	2.82	128.40
5	3.00	143.70
7	3.17	142.80
8	3.37	151.79
3	5.05	128.46
5	5.20	141.11
7	5.40	143.87
8	5.57	142.18
3	10.20	88.59
5	10.40	133.33
7	10.63	141.60
8	10.83	141.98
3	60.20	104.56
5	60.43	117.18
7	60.65	136.22
8	60.85	148.08

Blank Conc (mg/l)

0.44

Recycle Conc (mg/l)

1	335.90
2	258.37
3	n/a

Non-Settleable Solids (mg/l)

1	38.15
2	25.73

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	16.75	299.07
2	1.00	18.5	193.94
3	3.00	15.75	349.95
4	3.00	14.75	262.27
1	10.00	16.5	426.87
2	60.00	16.5	367.27
3	5.00	16.25	324.39

Experiment 3: 6/10/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.25	175.27
5	0.50	186.29
7	0.70	264.17
8	0.90	374.35
3	1.32	141.53
5	1.57	156.28
7	1.80	177.05
8	2.00	182.95
3	3.02	132.33
5	3.17	185.16
7	3.37	153.97
8	3.57	154.58
3	5.25	123.36
5	5.47	141.31
7	5.67	142.28
8	5.92	146.01
3	10.45	119.85
5	10.75	132.05
7	11.00	136.51
8	11.25	136.47
3	59.95	85.94
5	60.15	129.37
7	60.33	154.73
8	60.57	152.67

Blank Conc (mg/l)

n/a

Recycle Conc (mg/l)

1	288.89
2	220.08
3	286.38

Non-Settleable Solids (mg/l)

1	n/a
2	33.11

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	15.25	351.10
2	1.00	17	238.82
3	3.00	16	412.69
4	5.00	16.25	255.59
1	10.00	16.5	536.23
2	60.00	16.75	249.68
3	3.00	16.88	342.37

Experiment 4: 6/11/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.38	107.39
5	0.52	57.41
7	0.75	218.10
8	0.97	346.80
3	1.35	29.23
5	1.53	47.64
7	1.72	n/a
8	1.88	91.20
3	2.58	15.23
5	2.83	20.00
7	2.98	16.27
8	3.45	22.14
3	4.88	n/a
5	5.02	8.24
7	5.18	9.41
8	5.35	8.94
3	9.97	7.20
5	10.17	7.02
7	10.35	5.87
8	10.55	8.05

Blank Conc (mg/l)

1.06

Recycle Conc (mg/l)

1	156.50
2	256.76
3	207.08

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	15.5	315.31
2	1.00	15.75	116.13
3	3.00	15.5	213.62
4	5.00	15.5	116.02
1	10.00	16.38	463.14
2	1.00		124.84

Experiment 5: 6/11/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.27	193.77
5	0.47	263.57
7	0.70	312.81
8	0.88	292.69
3	1.08	242.91
5	1.27	262.73
7	1.42	248.18
8	1.58	277.07
3	2.85	228.00
5	2.98	248.35
7	3.15	256.61
8	3.32	261.16
3	4.95	209.16
5	5.13	226.82
7	5.30	248.35
8	5.48	#DIV/0!
3	11.22	170.82
5	11.40	221.97
7	11.57	240.63
8	11.77	247.06
3	59.95	140.08
5	60.17	221.11
7	60.35	255.56
8	60.63	266.14

Blank Conc (mg/l)

3.94

Recycle Conc (mg/l)

1	305.28
2	286.85
3	269.55

Non-Settleable Solids (mg/l)

1	56.74
2	43.35

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		339.48
2	1.00		291.85
3	3.00		384.09
4	5.00	16.25	312.08
1	10.00	14.5	442.47
2	60.00	16	387.99
3	0.00	16.25	267.18

Experiment 6: 6/12/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.20	254.96
5	0.42	243.51
7	0.58	319.48
8	0.72	338.27
3	0.93	254.03
5	1.13	260.25
7	1.32	272.65
8	1.52	242.03
3	2.90	231.75
5	3.07	233.72
7	3.22	255.19
8	3.38	267.18
3	5.00	212.08
5	5.17	235.12
7	5.33	246.69
8	5.48	254.55
3	9.90	179.92
5	10.07	215.29
7	10.25	246.30
8	10.42	257.14
3	59.95	119.69
5	60.08	212.70
7	60.25	255.34
8	60.47	244.62

Blank Conc (mg/l)

0.71

Recycle Conc (mg/l)

1	283.33
2	290.71
3	n/a

Non-Settleable Solids (mg/l)

1	34.62
2	49.26

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	16.25	322.97
2	1.00	15.75	290.85
3	3.00	15.25	369.12
4	5.00	15.75	339.92
1	10.00	16.5	464.36
2	60.00	16.5	411.72
3	60.00	16	454.04

Experiment 7: 6/12/98 Long Column Initial Height=8'

Long column data

Port	Time (min)	Conc (mg/l)
3	0.25	188.76
5	0.45	241.44
7	0.63	n/a
8	0.83	357.87
3	1.35	145.77
5	1.50	155.06
7	1.63	196.83
8	3.25	157.56
3	2.73	135.02
5	2.87	147.46
7	3.02	157.53
8	1.82	184.07
3	4.83	123.17
5	4.98	136.89
7	5.13	149.80
8	5.28	137.08
3	9.95	114.02
5	10.10	129.96
7	10.30	139.26
8	10.37	150.20
3	60.48	86.94
5	60.75	129.59
7	60.93	155.98
8	61.12	159.07

Blank Conc (mg/l)

	1.07
	1.08

Recycle Conc (mg/l)

1	298.74
2	327.46
3	257.99

Non-Settleable Solids (mg/l)

1	27.31
2	26.78

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	15.25	347.42
2	1.00	15.75	216.54
3	3.00	15.50	359.04
4	5.00	16.25	259.15
1	10.00	16.25	467.11
2	60.00	16.5	256.56
3	10.00	15.75	327.98

Experiment 8: 6/14/98 Long Column Initial Height=7'11.6"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.22	60.22
5	0.35	153.90
7	0.50	388.99
8	0.62	n/a
3	1.07	n/a
5	1.22	78.54
7	1.35	130.36
8	1.52	120.44
3	2.87	9.96
5	3.00	25.61
7	3.15	23.18
8	3.32	37.04
3	5.00	6.74
5	5.15	7.17
7	5.30	10.61
8	5.47	16.05
3	9.80	4.58
5	9.95	5.91
7	10.10	7.09
8	10.23	3.76

Blank Conc (mg/l)

3.38

Recycle Conc (mg/l)

1	290.98
2	238.26
3	310.80

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	15.25	291.05
2	1.00	16.125	160.11
3	3.00	15.5	197.34
4	5.00	16	143.87
1	10.00	15.5	445.89
2	5.00	16.25	152.55

Experiment 9: 6/15/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.20	157.87
5	0.35	189.24
7	0.50	329.32
8	0.70	345.31
3	1.15	126.80
5	1.27	155.65
7	1.38	145.53
8	1.53	201.98
3	2.80	93.42
5	2.93	128.95
7	3.07	137.36
8	3.22	144.62
3	4.80	94.09
5	4.95	114.45
7	5.08	128.90
8	5.27	116.97
3	9.72	82.61
5	9.90	105.62
7	10.05	118.50
8	10.22	118.22
3	59.92	63.71
5	60.10	111.11
7	60.28	142.05
8	60.47	136.36

Blank Conc (mg/l)

	0.77
	1.79

Recycle Conc (mg/l)

1	257.66
2	235.42
3	282.44

Non-Settleable Solids (mg/l)

1	24.62
2	21.84

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
2	0.00	16.25	206.04
4	1.00	17	265.51
1	3.00		485.70
3	5.00	16.25	308.30
2	10.00	16	255.21
4	60.00	16.75	279.57
1	3.00	16	447.19

Experiment 10: 6/15/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.25	260.34
5	0.42	302.07
7	0.58	327.98
8	0.77	347.62
3	1.10	257.92
5	1.30	285.56
7	1.47	276.47
8	1.63	291.76
3	2.83	229.20
5	2.97	260.59
7	3.12	276.15
8	3.27	272.16
3	n/a	n/a
5	4.88	246.72
7	5.05	256.32
8	5.23	264.57
3	9.87	187.68
5	10.07	236.80
7	10.15	258.40
8	10.32	257.33
3	59.80	131.82
5	60.00	212.00
7	60.18	286.82
8	60.33	n/a

Blank Conc (mg/l)

0.80

Recycle Conc (mg/l)

1	287.92
2	298.82
3	267.19

Non-Settleable Solids (mg/l)

1	48.05
2	46.56

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	17.00	284.23
1	1.00	14.5	329.89
1	3.00	16.50	391.54
1	5.00		422.62
1	10.00	16.75	454.89
1	1.00	16.5	328.06
1	60.00	16.25	487.68

Experiment 11: 6/16/98 Long Column Initial Height=7'11.5"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.25	177.26
5	0.42	n/a
7	0.58	305.33
8	0.73	356.09
3	1.20	144.72
5	1.33	169.35
7	1.47	168.08
8	1.63	205.14
3	2.77	133.05
5	2.88	142.26
7	3.03	156.30
8	3.18	160.23
3	4.75	112.60
5	4.92	130.68
7	5.07	137.36
8	5.22	139.53
3	9.72	103.77
5	9.87	116.72
7	10.05	131.13
8	10.22	134.69
3	59.45	79.10
5	59.62	118.08
7	59.77	138.31
8	59.95	144.65

Blank Conc (mg/l)

-0.38

Recycle Conc (mg/l)

1	237.24
2	239.32
3	276.47

Non-Settleable Solids (mg/l)

1	30.42
2	28.99

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		290.21
1	1.00	17	413.54
1	3.00	16.75	381.56
1	5.00	16.5	429.53
1	10.00	15.5	487.29
1	0.00	17	290.94
1	60.00	16.38	469.90

Experiment 12: 6/16/98 Long Column Initial Height=7'11.6"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.23	62.64
5	0.37	152.96
7	0.50	291.61
8	0.65	354.75
3	0.95	26.29
5	1.08	68.06
7	1.23	113.62
8	1.37	138.08
3	2.65	15.98
5	2.80	10.11
7	2.97	35.88
8	3.13	48.69
3	5.30	10.40
5	5.43	9.09
7	5.57	11.67
8	5.70	13.85
3	9.78	8.08
5	9.92	6.44
7	10.05	5.15
8	10.22	11.35

Blank Conc (mg/l)

3.57

Recycle Conc (mg/l)

1	302.26
2	274.27
3	299.62

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		269.22
1	1.00	16.5	453.78
1	3.00	16.75	533.85
1	5.00	17	529.42
1	10.00	16.75	490.94
1	10.00	17	392.67

Experiment 13: 6/17/98 Long Column Initial Height=7'11.5"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.48	50.00
5	0.62	123.08
7	0.75	166.28
8	0.90	253.72
3	1.27	24.24
5	1.40	54.51
7	1.53	98.80
8	1.67	110.98
3	2.85	8.63
5	3.00	3.40
7	3.20	n/a
8	3.37	43.56
3	4.90	5.90
5	5.05	7.63
7	5.18	9.62
8	5.37	10.64
3	10.13	3.18
5	10.30	5.56
7	10.42	4.12
8	10.57	8.40

Blank Conc (mg/l)

3.96

Recycle Conc (mg/l)

1	254.29
2	304.02
3	n/a

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		310.00
1	1.00	16.00	478.76
1	3.00	16.50	518.55
1	5.00	17.00	455.03
1	5.00	16.50	516.27
1	10.00	16.75	553.19

Experiment 14: 6/17/98 Long Column Initial Height=8'

Long column data

Port	Time (min)	Conc (mg/l)
3	0.23	270.33
5	0.38	283.14
7	0.52	331.52
8	0.72	333.86
3	1.23	264.20
5	1.40	282.87
7	1.53	n/a
8	1.68	299.23
3	2.82	258.61
5	3.03	268.60
7	3.18	293.49
8	3.33	292.28
3	4.87	236.96
5	5.02	264.37
7	5.15	278.60
8	5.28	284.56
3	10.22	217.99
5	10.38	253.01
7	10.57	282.73
8	10.75	294.80
3	59.47	138.24
5	59.67	227.84
7	59.83	273.91
8	59.97	291.97

Blank Conc (mg/l)

0.78

Recycle Conc (mg/l)

1	285.28
2	299.56
3	n/a

Non-Settleable Solids (mg/l)

1	46.69
2	56.81

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		262.09
1	1.00	16.50	384.19
1	3.00	16.50	458.46
1	5.00	17.25	509.18
1	3.00	16.50	408.54
1	10.00	17.00	469.89
1	60.00		541.58

Experiment 15: 6/17/98 Long Column Initial Height=8'

Long column data

Port	Time (min)	Conc (mg/l)
3	0.20	55.47
5	0.38	167.86
7	0.52	345.45
8	0.68	386.69
3	1.15	31.18
5	1.35	44.85
7	1.48	103.45
8	1.63	86.17
3	2.80	16.41
5	2.93	21.88
7	3.07	38.19
8	3.20	46.85
3	4.78	12.06
5	4.92	12.32
7	5.05	8.05
8	5.20	19.49
3	9.87	10.73
5	10.03	7.98
7	10.17	5.19
8	10.35	12.20

Blank Conc (mg/l)

0.40

Recycle Conc (mg/l)

1	235.81
2	275.83
3	282.84

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		269.33
1	1.00	16.50	492.50
1	3.00	17.00	470.94
1	5.00	16.00	493.68
1	1.00		482.38
1	12.00	16.75	517.29